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COMPUTER SIMULATION OF MUX BUS VOLTAGE WAVEFORMS UNDER STEADY STATE CONDITIONS

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Digital techniques involving multiplex busing are being advocated in many quarters as a means of satisfying the need for greater reliability, decreased modification cost, and simplified maintenance of airborne avionics systems. This paper documents efforts to develop a computer simulation of a shielded, twisted pair cable multiplex bus with multiple subscribers using steady state equations. The simulation predicts

voltage waveforms, driving point impedances, and power distributions for systems compatible with MIL-STD-1553 (USAF). Excellent agreement has been found between laboratory observations and the computer simulation, validating this approach.

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SECTION I

INTRODUCTION

The bulk of information available regarding the characteristics and performance of multiplex (MUX) bus systems is empirical in nature. Consequently, designers and system planners have had to hedge when asked to estimate voltage waveforms, driving point impedances and power distribution for a proposed multiplex bus system. Either educated guesses based on past experience are made or a laboratory duplicate of the candidate system is built on which the required parameter measurements can be made. When relying on educated guesses the possibility of error has to be tolerated, especially when the system under consideration is radically different from the majority of existing designs. While measurements on a laboratory system generally give more trustworthy results, they may require considerable time and expense. This paper describes a third alternative, computer simulation, which offers a reasonable compromise between the two extremes.

The use of computer simulation rather than physical realization offers several significant advantages. First, it greatly simplifies system analysis when the bus topology must be changed to investigate various cable routing schemes. In the initial design phase when the optimum bus arrangement and routing is usually uncertain, the use of simulation could eliminate the need for costly laboratory mock-ups. Also, a knowledge of the system's sensitivity to variations in cable or component parameters is of considerable importance but difficult to obtain in the laboratory. Finally, a need for worst-case information in many cases leads to the application of physical "cut and try" analysis. If applied to a complex MUX Bus, this method would likely be excessively expensive and time consuming.

The computer simulation described in this paper may be applied to any MUX Bus which meets the architectural constraints of MIL-STD-1553 (1) (see Section III). Also, because of the computer program's reliance on steady-state analysis, systems which exhibit significant transient response cannot be completely simulated. However, laboratory investigation has shown that the transient response is not significant when the bus architecture of MIL-STD-1553 is used.

SECTION II

CONCLUSIONS

As a result of this investigation, several observations of potential importance to MUX Bus system planners have been made.

1) A digital computer steady-state simulation of MIL-STD-1553 compatible multiplex buses has been developed and tested against laboratory measurements, yielding acceptable levels of agreement. This simulation provides driving point impedances, power distributions and voltage waveforms at various locations throughout the bus. The ability to change both system architecture and component parameters in software makes this simulation a valuable tool for analysis of proposed MUX Bus configurations.

2) Laboratory observations and simulation results suggest that an engineering trade-off must be made between power transferred from transmitter to receiver along the bus and the level of signal distortion in the received waveform. Power transfer is greatest when the stub driving point impedances are low. However, low stub impedances increase the loading on tne bus thereby causing an increase in waveform distortion. Computer simulation may help to make this trade-off a more rational one.

3) It has been found that under certain situations normal manufacturing variation of component parameters may drastically alter bus performance. The only tractable method available for determining these sensitivities appears to be computer simulation.

SECTION III

MIL-STD-1553 (USAF)

In an effort to define operational characteristics and avionics interfaces for multiplex buses used in intra-aircraft signaling the Air Force Aeronautical Systems Division (AFASD) has published a document entitled "Military Standard for Aircraft Multiplex Data Bus," (MIL-STD-1553 (USAF)). The following is a listing of characteristics defined in the standard which are relevant to this discussion.

Transmission Medium:	Twisted, shielded pair, Zo = 71 ohms
Bus Discipline:	Command/Response, half duplex; bus control exercised by a Bus Control Unit
Transmission Bit Rate:	1 Megabit per second
Modulation:	PCM, using Manchester II code
Timing:	Asynchronous, carried by Manchester Code
Number of Terminals:	33 maximum including Bus Control Unit
MUX Bus Length:	300 ft. max.
Length of Terminal Stubs:	20 ft. max.
Short Circuit Protection:	54 ohms resistor in each conductor of the stub pair.
Stub Driving Point Impedance (Receive Mode):	$\geq$ 6800 ohms dc to 100 kHz $\geq$ 2000 ohms 100 kHz to 1 MHz

Figure 1 depicts the bus architecture, defined by MIL-STD-1553, which was used as a basis for the simulation. For the cases examined in this paper, the following values were chosen for the variables of Figure 1:

Bus Length:	$L_{(bus)} = 250'$
Number of Stubs:	N = 20

Length of each Stub:	$L_{(stub)} = 20'$	
Transformer Turns Ratios:	N1:N2 1 1:1	Pulse Engineering, Inc.
	N3:N4 = 1:1	Type 5163
Isolation Resistances:	R1 = 54 ohms	
	R2 = 0 ohms	
Receiver Input Impedance:	6800 ohms	

To assure that reasonable values were chosen for the cable characteristics employed in the simulation, Haveg Industries type LE-572-0003/0002 cable was used as a guide. This cable, a lightweight version of RG-108A, has been recommended for use in multiplex bus applications on the B-1 aircraft by North American Rockwell. Laboratory measurements on samples of this cable produced the following parameter values:

C = 21.8 pf per foot,

L = .109 μh per foot,

R = .0288 ohms per foot,

Zo = 71 ohms

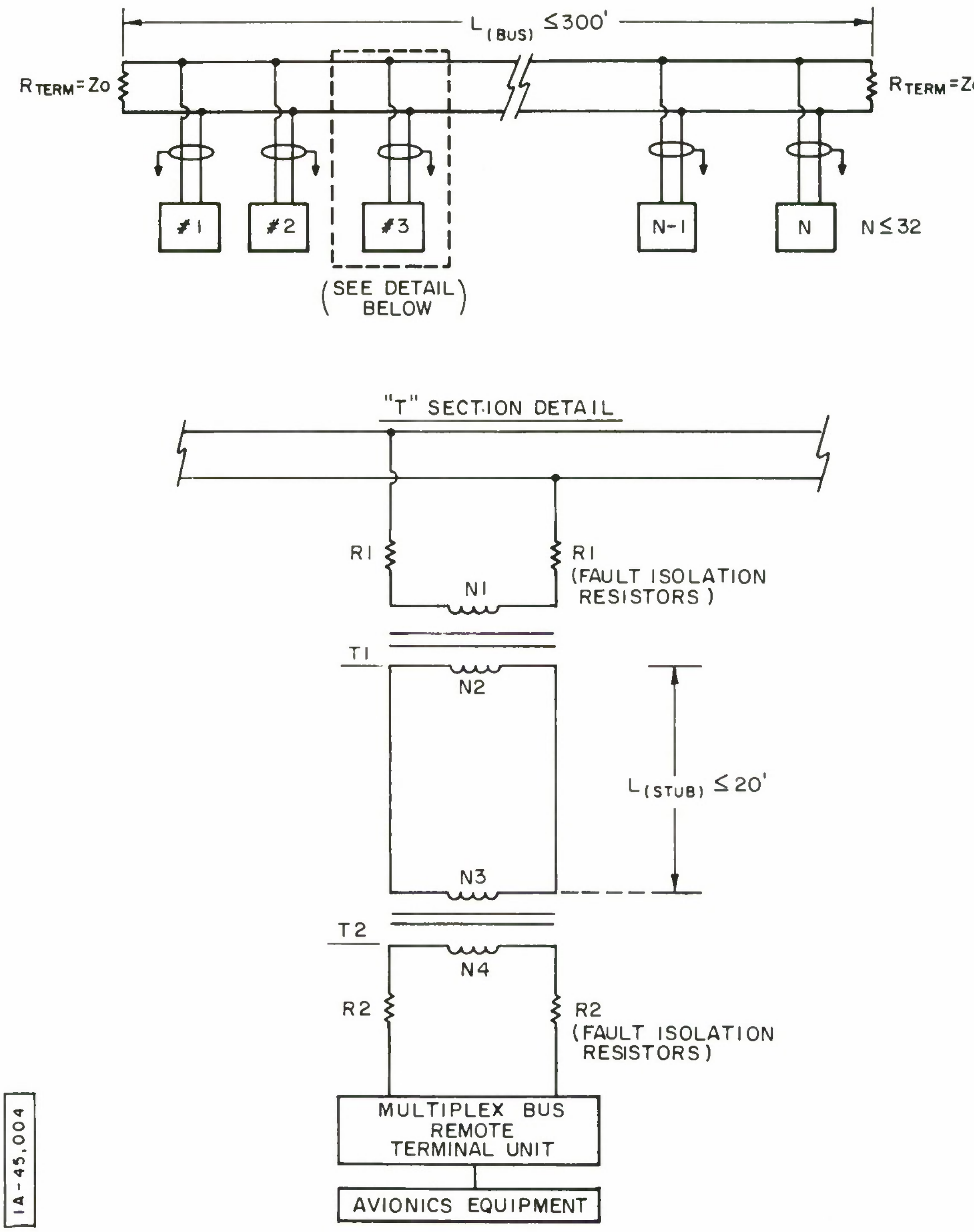

Figure 1 MUX-BUS ARCHITECTURE

SECTION IV

CELL APPROACH

Definition

In the MUX Bus system of MIL-STD-1553, each Multiplex Bus Remote Terminal Unit (RTU, see Figure 1) is capable of transmitting information onto the bus. Of course, only one may transmit at a time. If the computer simulation is to be sufficiently flexible to allow this type of operation, some form of modularization is required. The "T" section of Figure 1 will be defined as a basic module, or "cell", of the MUX Bus. Each cell may contain one RTU, two transformers, four fault isolation resistors and three sections of shielded, twisted pair cable. In addition, the first (leftmost) and last (rightmost) cells each contain a bus termination resistor whose value is equal to the cable's characteristic impedance, Zo. The division point between adjacent cells is chosen such that only N cells, where N is the number of stubs, are required to represent a given MUX Bus.

Circuit Analysis of a Cell

Transmitting Cell

Consider the cell shown in Figure 2 whose RTU is transmitting onto the bus. Complex impedances $\overrightarrow{Z(1)}$ and $\overrightarrow{Z(2)}$, the driving point impedances seen looking into the adjacent cells, will be assumed known for the moment. The first step taken by the simulation is to determine values for $\overrightarrow{Z(4)}$ and $\overrightarrow{Z(5)}$ by use of the following relationships:(3)

$$\frac{\overrightarrow{Z(5)}}{Zo} = \frac{\overrightarrow{Z(2)}\ \text{Cosh}(\vec{\gamma}\cdot L2) + Zo\ \text{Sinh}(\vec{\gamma}\cdot L2)}{Zo\ \text{Cosh}(\vec{\gamma}\cdot L2) + \overrightarrow{Z(1)}\ \text{Sinh}(\vec{\gamma}\cdot L2)} \qquad (1)$$

$$\frac{\overrightarrow{Z(4)}}{Zo} = \frac{\overrightarrow{Z(1)}\ \text{Cosh}(\vec{\gamma}\cdot L1) + Zo\ \text{Sinh}(\vec{\gamma}\cdot L1)}{Zo\ \text{Cosh}(\vec{\gamma}\cdot L1) + \overrightarrow{Z(1)}\ \text{Sinh}(\vec{\gamma}\cdot L1)} \qquad (2)$$

where: $\vec{\gamma}$ = propagation constant of the cable

Zo = characteristic impedance of the cable

Impedances $\overrightarrow{Z(6)}$, $\overrightarrow{Z(8)}$, $\overrightarrow{Z(3)}$, $\overrightarrow{Z(9)}$, and $\overrightarrow{Z(7)}$ are obtained in a similar manner using the above relationship combined with steady state circuit analysis and the transformer lumped component

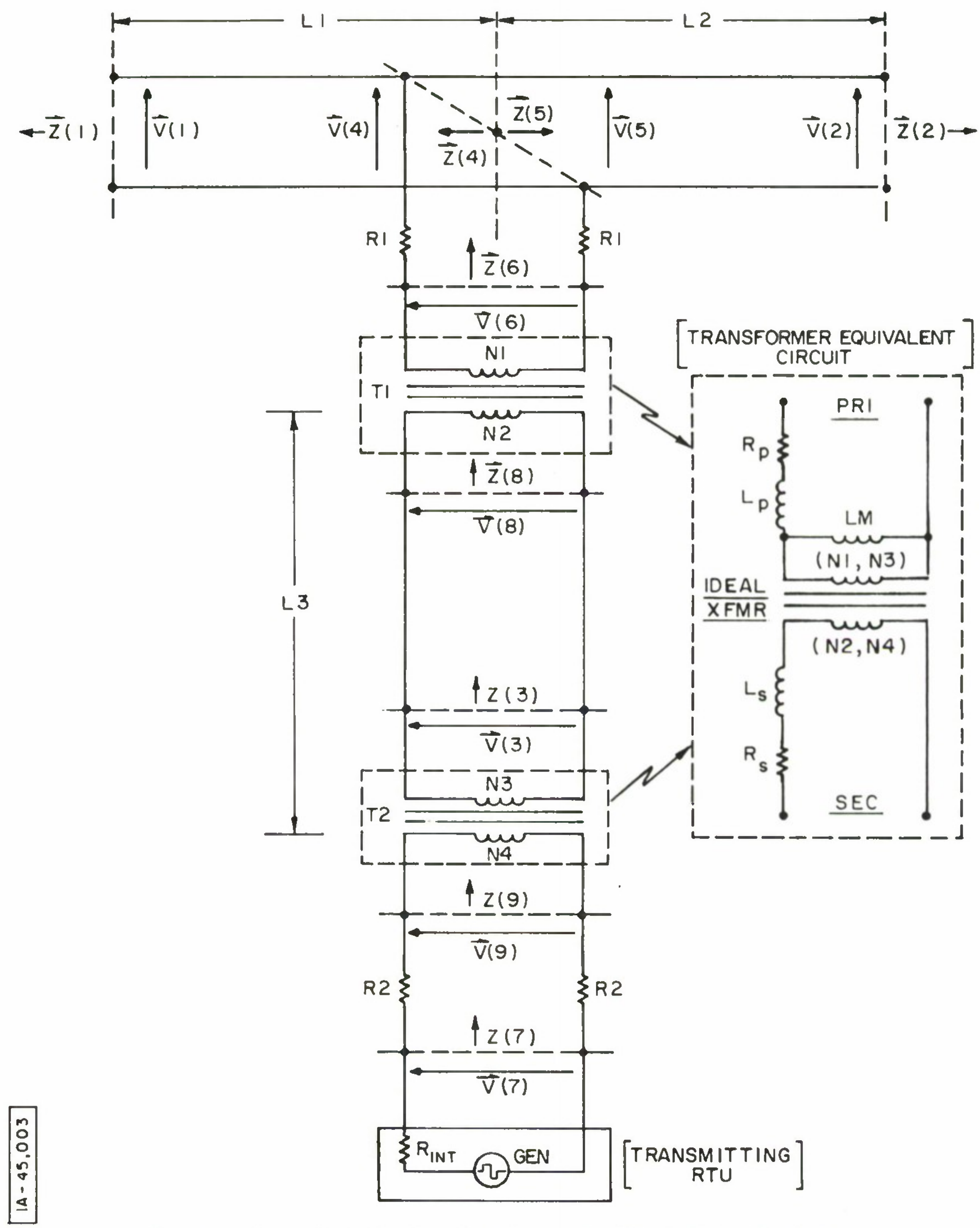

Figure 2 TRANSMITTING CELL SCHEMATIC DIAGRAM

equivalent circuit. This procedure must be repeated at each frequency which corresponds to an harmonic component of the RTU output, voltage $\vec{V}(7)$ of Figure 2. The waveform in Figure 3 is a normalized representation of this unit's output voltage. The Fourier series for this voltage is:

$$\vec{V}(7) = \sum_{n=1}^{\infty} C_n \cos(nwt) \qquad (3)$$

where:

$$C_n = \left[\frac{\mathrm{Sin}\ \pi \frac{nt1}{T}}{\pi \frac{nt1}{T}}\right] \left[\frac{\mathrm{Sin}\ \pi \frac{n(to + t1)}{T}}{\pi \frac{n(to + t1)}{T}}\right]$$

n = harmonic number = 1, 3, 5, . . .

Therefore, as many odd harmonies of the fundamental frequency as accuracy requirements dictate will have to be considered in the impedance calculations. [NOTE: For rise/fall times consistant with MIL-STD-1553 and a 1 MHz fundamental frequency, approximately six or more odd harmonies should be considered.]

After the impedances $\vec{Z}(1)$ through $\vec{Z}(9)$ are known at each applicable frequency, the next step is to apply each harmonic component of the RTU output voltage waveform $\vec{V}(7)$ to the cell. Calculation of $\vec{V}(9)$ and $\vec{V}(3)$ from $\vec{V}(7)$ is fairly straightforward and will not be explained in detail. Voltage $\vec{V}(8)$ is found by using voltage $\vec{V}(3)$ and the following equation (3):

$$\vec{V}(8) = \vec{V}(3)\ \left[\mathrm{Cosh}(\vec{\gamma}\cdot L3) - (ZO/\vec{Z}(3))\ \mathrm{Sinh}(\vec{\gamma}\cdot L3)\right] \qquad (4)$$

Using this relationship, the transformer model, and AC circuit analysis, voltages $\vec{V}(6)$, $\vec{V}(4)$, $\vec{V}(5)$, $\vec{V}(1)$ and $\vec{V}(2)$ may be obtained. As with the impedance calculations, this procedure must be repeated for each of the relevant harmonic frequencies.

The final step in the analysis of the transmitting cell is to determine the composite voltage waveforms, harmonic power distributions, and composite power distributions at each of the nine points shown in Figure 2. The composite voltage waveform at point Q is found by:

$$\underset{[\text{composite voltage}]}{v_Q(t)} = \sum_{(n=1,3,5\ldots)}^{NN} \vec{V}_n(Q)\ \mathrm{Cos}(nwt) \qquad (5)$$

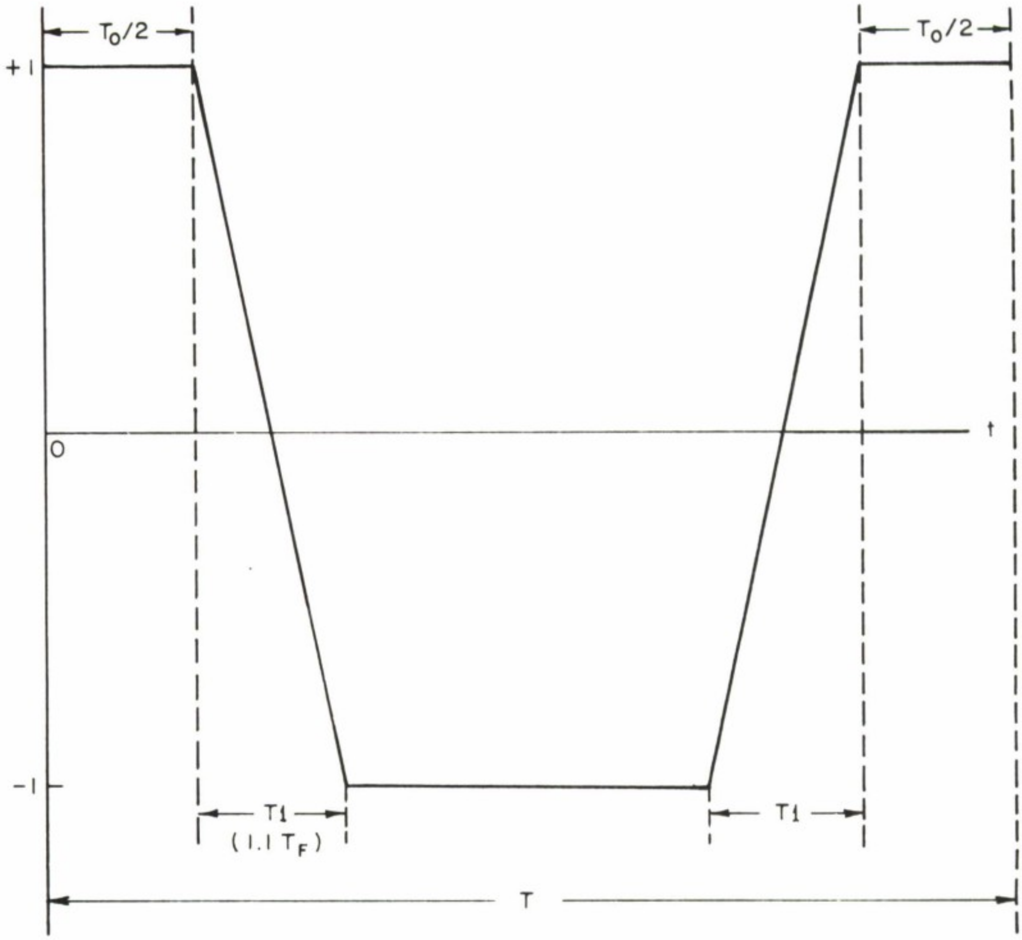

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Figure 3 INPUT PULSE WAVEFORM (NORMALIZED)

where: n = harmonic number

NN = highest odd harmonic considered

Q = position number (1,2,...,9)

$\vec{V_n}(Q)$ = voltage phasor at point Q for frequency n

In the computer program this summation is done at discrete time increments from t=0 to t=T, where T is the period of the fundamental frequency.

The impedances previously calculated are actually driving point impedances at each of the measurement points indicated in Figure 2. Using this fact, along with the corresponding harmonic voltages, leads to the following expression for average harmonic power at point Q:

$$P_n(Q) = \frac{|\vec{V_n}(Q)|^2}{2|\vec{Z_n}(Q)|} \cos(\theta) \quad \begin{bmatrix} \text{average} \\ \text{harmonic} \\ \text{power} \end{bmatrix} \tag{6}$$

where: θ = angle of impedance $\vec{Z_n}(Q)$

To find the composite average power at point Q requires a summation of the average harmonic powers, i.e.:

$$P_Q = \sum_{n=1,3,5}^{NN} P_n(Q) \quad \begin{bmatrix} \text{composite} \\ \text{average} \\ \text{power} \end{bmatrix} \tag{7}$$

The only matter not covered at this point is where values for the previously assumed impedances $\vec{Z}(1)$ and $\vec{Z}(2)$ come from. This question, addressed in the next two sections, is the basis for the **flexibility** inherent in the cell approach.

Receiving Cell

Within the framework of MIL-STD-1553, only one RTU can transmit information onto the bus at any given time. Consequently, (N-1) cells (where N is the number of RTU's) are considered to be receiving cells. For the purpose of this discussion these (N-1) cells will be defined as either Left Cells (LCELL) or Right Cells (RCELL), depending on their location relative to the transmitting cell.

Right Cells. Figure 4 depicts impedance and voltage conventions within an RCELL. These conventions are applied to all RCELL's except the last, or rightmost cell. The difference in RCELL(LAST) is that $\vec{Z}(2)$ is actually equal to RTERM, a known constant, as can be seen from Figure 1. The significance of this point will be discussed in the section on chaining of cells.

As in the transmitting cell case, the first step in the simulation of an RCELL is to determine the driving point impedances throughout the cell. Assuming that the value of $\vec{Z}(2)$ is known:

$$\frac{\vec{Z}(5)}{Zo} = \frac{\vec{Z}(2)\ \mathrm{Cosh}(\vec{\gamma}\cdot L2) + Zo\ \mathrm{Sinh}(\vec{\gamma}\cdot L2)}{Zo\ \mathrm{Cosh}(\vec{\gamma}\cdot L2) + \vec{Z}(1)\ \mathrm{Sinh}(\vec{\gamma}\cdot L2)} \tag{8}$$

Note that this equation has the same form as Equation 1.

The receiving input impedance of the RTU, $\vec{Z}(7)$, is known. Therefore, impedances $\vec{Z}(9)$ and $\vec{Z}(3)$ can be readily calculated. To find $Z(8)$, $\vec{Z}(3)$ is used in the following equation:

$$\frac{\vec{Z}(8)}{Zo} = \frac{\vec{Z}(3)\ \mathrm{Cosh}(\vec{\gamma}\cdot L3) + Zo\ \mathrm{Sinh}(\vec{\gamma}\cdot L3)}{Zo\ \mathrm{Cosh}(\vec{\gamma}\cdot L3) + \vec{Z}(3)\ \mathrm{Sinh}(\vec{\gamma}\cdot L3)} \tag{9}$$

Solving for $\vec{Z}(6)$ using the transformer model and $\vec{Z}(8)$ allows the following relation for $\vec{Z}(4)$:

$$\vec{Z}(4) = \left[\vec{Z}(6) + 2\cdot R1\right] || \vec{Z}(5) \tag{10}$$

With the value of $\vec{Z}(4)$ determined, $\vec{Z}(1)$ can be found by:

$$\frac{\vec{Z}(1)}{Zo} = \frac{\vec{Z}(4)\ \mathrm{Cosh}(\vec{\gamma}\cdot L1) + Zo\ \mathrm{Sinh}(\vec{\gamma}\cdot L1)}{Zo\ \mathrm{Cosh}(\vec{\gamma}\cdot L1) + \vec{Z}(4)\ \mathrm{Sinh}(\vec{\gamma}\cdot L1)} \tag{11}$$

An important point to be made here is that $\vec{Z}(1)$ of this cell is identically equal to $\vec{Z}(2)$ of the preceding cell on the left. Conversely, $\vec{Z}(2)$ is equal to $\vec{Z}(1)$ of the following cell on the right. This transference of impedance values across cell boundaries provides a "daisy-chaining" effect, supplying values for $\vec{Z}(2)$ of the transmitter cell, which was assumed known in the previous discussion.

The next step in the analysis is to determine the voltages within the cell. Here the input voltage is considered to be $\vec{V}(1)$, as opposed to $\vec{V}(7)$ in the transmitting cell case. Values for this

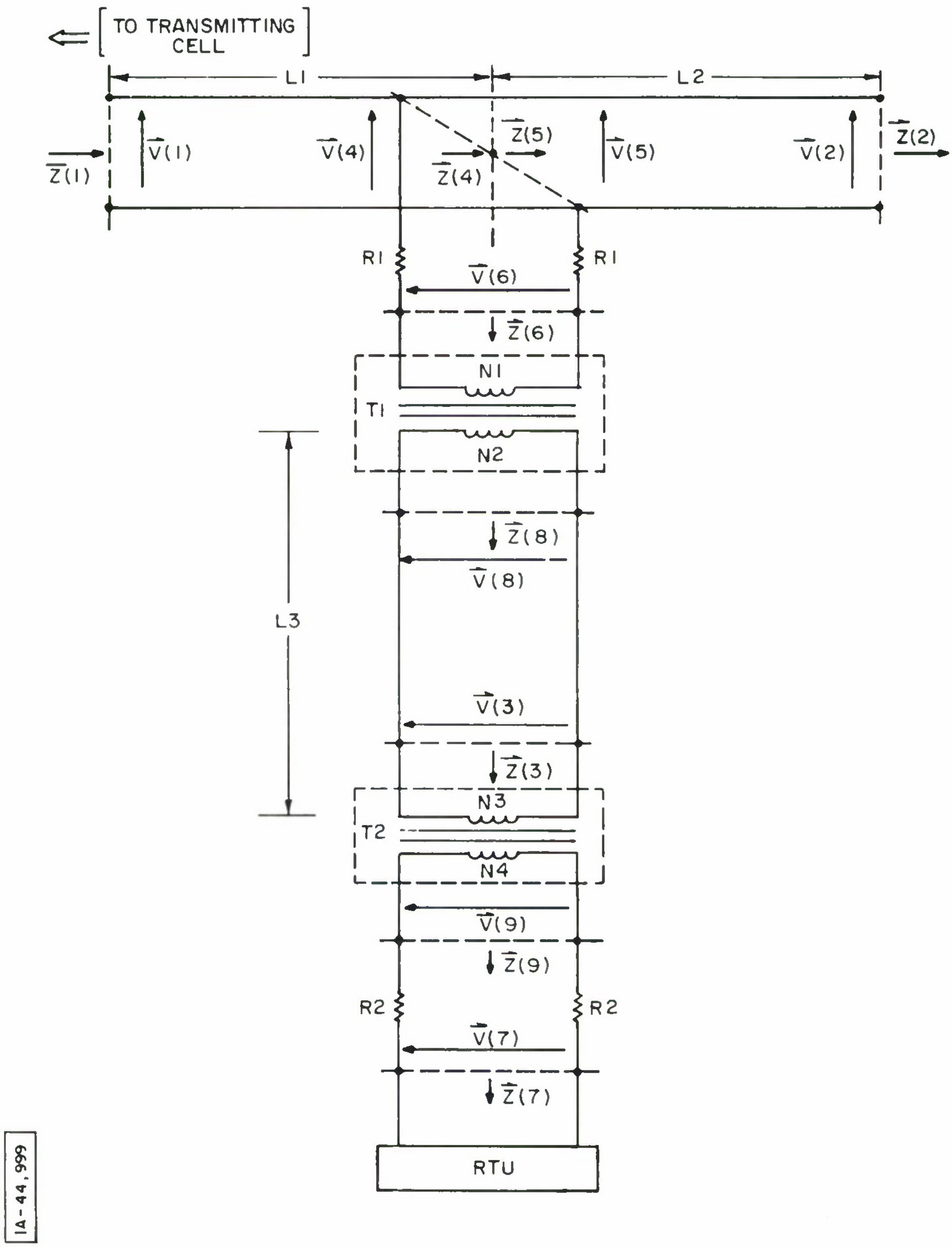

Figure 4 RIGHT CELL SCHEMATIC DIAGRAM

voltage at the various harmonics are supplied by $\vec{V}(2)$ of the cell on the immediate left. To find $\vec{V}(4)$ apply $\vec{V}(1)$ to:

$$\vec{V}(4) = \vec{V}(1)\ [\mathrm{Cosh}(\vec{\gamma}\cdot L1) - (Zo/\vec{Z}(1))\ \mathrm{Sinh}(\vec{\gamma}\cdot L1)] \qquad (12)$$

which has the same form as Equation (2). Using the voltage divider relationship:

$$\vec{V}(6) = \vec{V}(4) \left[\frac{\vec{Z}(6)}{\vec{Z}(6) + 2\cdot R1}\right] \qquad (13)$$

Solving for $\vec{V}(8)$ using the transformer model leads to:

$$\vec{V}(3) = \vec{V}(8)\ [\mathrm{Cosh}(\vec{\gamma}\cdot L3) - (Zo/\vec{Z}(8))\ \mathrm{Sinh}(\vec{\gamma}\cdot L3)] \qquad (14)$$

Calculating $\vec{V}(9)$ from the transformer model, determine the received harmonic voltage at the RTU by:

$$\vec{V}(7) = \vec{V}(9) \left[\frac{\vec{Z}(7)}{\vec{Z}(7) + 2\cdot R2}\right] \qquad (15)$$

where: $\vec{Z}(7)$ represents the RTU receiver input impedance.

Returning to the bus/stub junction, apply the already determined value for $\vec{V}(4)$ to:

$$\vec{V}(2) = \vec{V}(4)\ \mathrm{Cosh}(\vec{\gamma}\cdot L2) - (Zo/\vec{Z}(5))\ \mathrm{Sinh}(\vec{\gamma}\cdot L2)$$

As mentioned earlier, voltage $\vec{V}(2)$ is the input voltage $\vec{V}(1)$ for the next RCELL to the right.

After the above procedures have been used to obtain the impedances and voltages for each harmonic, Equations 5, 6, and 7 are used to determine the composite voltage waveforms, average harmonic powers and average composite powers in each of the RCELLS.

<u>Left Cells</u>. The analysis of LCELLS, cells which are to the left of the transmitting cell, is analogous to RCELLS. The voltage and impedance conventions for this case are shown in Figure 5. Again, the difference in the first or leftmost cell is that $\vec{Z}(1)$ is equal to RTERM, a point that will be discussed further in the next section.

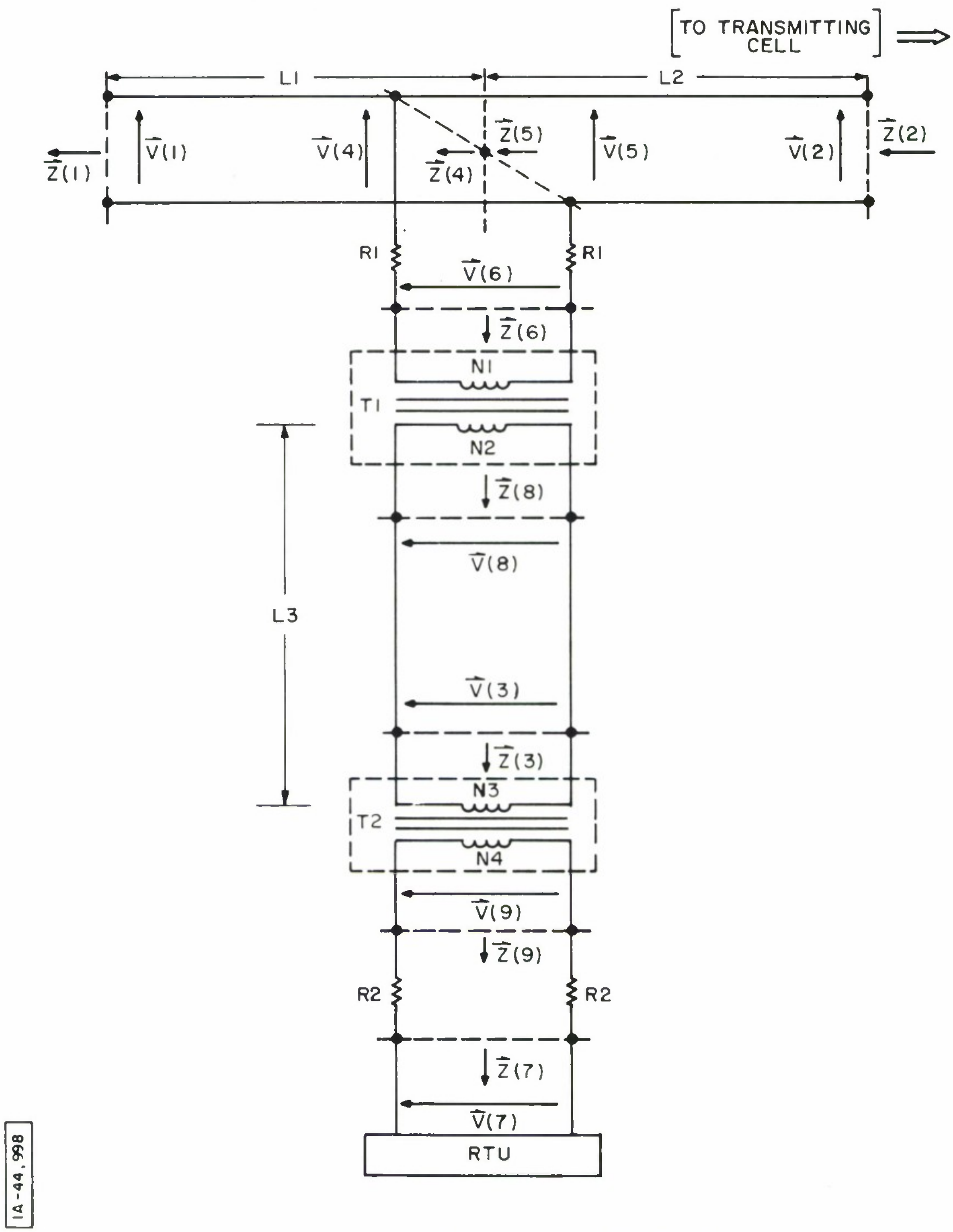

Figure 5 LEFT CELL SCHEMATIC DIAGRAM

In an LCELL the entry point for impedance calculations is $\vec{Z}(1)$. Values for this impedance at each harmonic frequency are obtained from $\vec{Z}(2)$ in the previous cell to the left. The order of calculation and methods used for an LCELL are the same as for an RCELL, i.e., $\vec{Z}(4)$ is found from $\vec{Z}(1)$ and the impedance translation equation; impedances $\vec{Z}(9)$, $\vec{Z}(3)$, $\vec{Z}(8)$, and $\vec{Z}(6)$ are obtained by using the transformer model, translation equation, and AC circuit analysis; $\vec{Z}(2)$ is determined by using the parallel combination of $\vec{Z}(4)$ and $\vec{Z}(5)$ in the translation equation. Calculation of voltages within an LCELL is also analogous to RCELL's. Instead of using $\vec{V}(1)$ as the input $\vec{V}(2)$ is used, but the procedure to be followed is equivalent. The main difference between the analysis of an LCELL and an RCELL is the direction of the driving point impedances, and the variables which are used as inputs to the cell. This similarity greatly decreases the complexity of the computer simulation program. Also, it allows complete flexibility of transmitter location--a fact that will be illustrated in the following section.

Chaining of Cells

Having considered each of the different cell types separately, the next step is to show how they may be connected to form a complete multiplex bus. Consider the system of Figure 6 in which a transmitting cell, LCELL, and RCELL have combined to form a three subscriber MUX Bus.

The first step in the analysis of this system is calulation of the driving point impedances. Referring to Cell 3 of Figure 6, an RCELL, several points about the cell boundaries become apparent. In the discussion of impedance calculations in an RCELL, mention was made that the value of $\vec{Z}(2)$ would be supplied by $\vec{Z}(1)$ of the next RCELL to the right. However, in this case $\vec{Z}(2)$ is actually equal to ZTERM, a known constant. Therefore, impedances $\vec{Z}(1)$ through $\vec{Z}(9)$ can be calculated for this cell without regard to any other cell. If there were more than one RCELL, the value just calculated for $\vec{Z}(1)$ in the rightmost cell would become the $\vec{Z}(2)$ of the next RCELL to the left, with the process continuing until all of the RCELLS had been considered. The same procedure is applied to the LCELLs except that calculation begins at the leftmost cell in which $\vec{Z}(1)$ = ZTERM and then progresses to the right until all LCELLS have been addressed. At that point the only driving point impedances not yet calculated would be those in the transmitting cell itself. Since there is no requirement that the number of LCELLS be equal to that of RCELLS the location of this remaining transmitting cell is completely arbitrary, a major advantage of the cell approach.

Returning to the transmitting cell of Figure 6, having found values for $\vec{Z}(2)$ of the LCELL on the immediate left and $\vec{Z}(1)$ of the RCELL on the immediate right, calculation of the driving point

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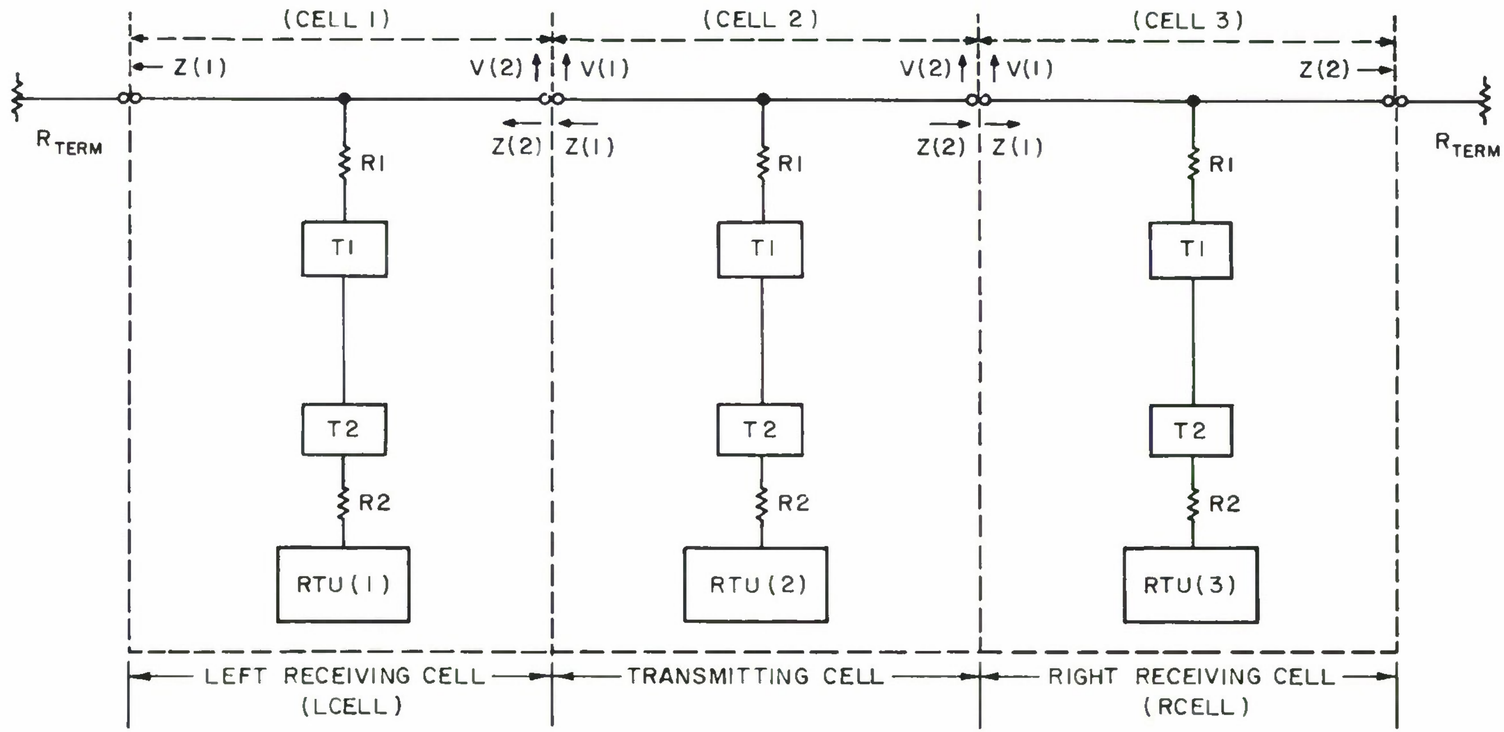

Figure 6 THREE CELL MULTIPLEX BUS

impedances within the transmitting cell follows the discussion in the Transmitting Cell Section.

Calculation of voltages throughout the bus proceeds in an analogous fashion but with an opposite direction of flow. Here the known values are the harmonic voltage amplitudes of the transmitting RTU's output waveform. Since all impedances have been determined, it is a simple matter to find the voltages within the transmitting cell using these amplitudes and the methods described previously. The values produced for voltages $\overrightarrow{V(1)}$ and $\overrightarrow{V(2)}$ become the inputs for the cells on the immediate left and right. The chaining process continues until all cell voltages on each side of the transmitting cell have been calculated. This sequence of operations may be summarized as follows: impedance calculations flow from the extremities of the mux-bus inward toward the transmitting RTU, while voltage calculations flow from the transmitting RTU outward toward the extremities of the bus.

With all voltages and impedances determined throughout the bus, calculation of the composite voltage waveforms, average harmonic powers, and average composite powers for each cell proceed as previously described in the Transmitting Cell Section.

SECTION V

MODEL VALIDATION

Validation of the MUX Bus simulation was accomplished in two stages. First, hand calculation and Smith chart analysis were used to check the driving point impedance and power distribution algorithms. Next, the voltage waveforms produced by the simulation were compared with oscillographs taken on a laboratory mock-up of a representative MUX Bus (2). The bus architecture used for this comparison, shown in Figure 7, had the characteristics discussed in Section III with one exception. Since it was possible to obtain only a limited supply of pulse transformers, the staggered transformer placement arrangement shown was adopted.

CASE I. The first comparison between laboratory waveforms and computer simulated plots is shown in Figure 8. The transmitter, a square wave pulse generator with output impedance equal to Zo, was connected to the end of Stub 6. The point at which voltage waveforms were to be compared was the junction between Stub 4 and the bus (labeled point "A" on Figure 7). The laboratory oscillograph of this waveform when isolation resistors R1 (Figure 1) were included in all cells is shown on the left of Figure 8. The dashed line on the plot directly above this picture is the computer simulation of the same voltage measured over one time period and normalized to a ± 1 volt transmitter signal excursion. The solid line in this plot is the simulation plotted waveform for the reference point defined by MIL-STD-1553 (see point "R", Figure 7). For the sake of clarity, the oscillograph of this reference waveform is not shown.

The right half of Figure 8 shows the comparison between laboratory and simulated waveforms for the same measurement point (point "A", Figure 7) when the isolation resistors R1 are shorted out. Again, the dashed line on the computer generated plot represents the simulations approximation of the waveform at this point.

When each set of comparisons is studied, two facts become apparent. First, the computer simulation plotted waveforms agree very closely with their associated laboratory oscillographs. This implies that the simulation is indeed valid. The second observation involves the utility of the isolation resistors (R1). As shown on the left of Figure 8, the observed and simulated waveforms are relatively free from distortion when R1 is included in each stub. However, as shown on the right, when this resistance is removed, there is a significant degree of "ringing" apparent. This distortion is a measure of the mutual interaction between stubs.

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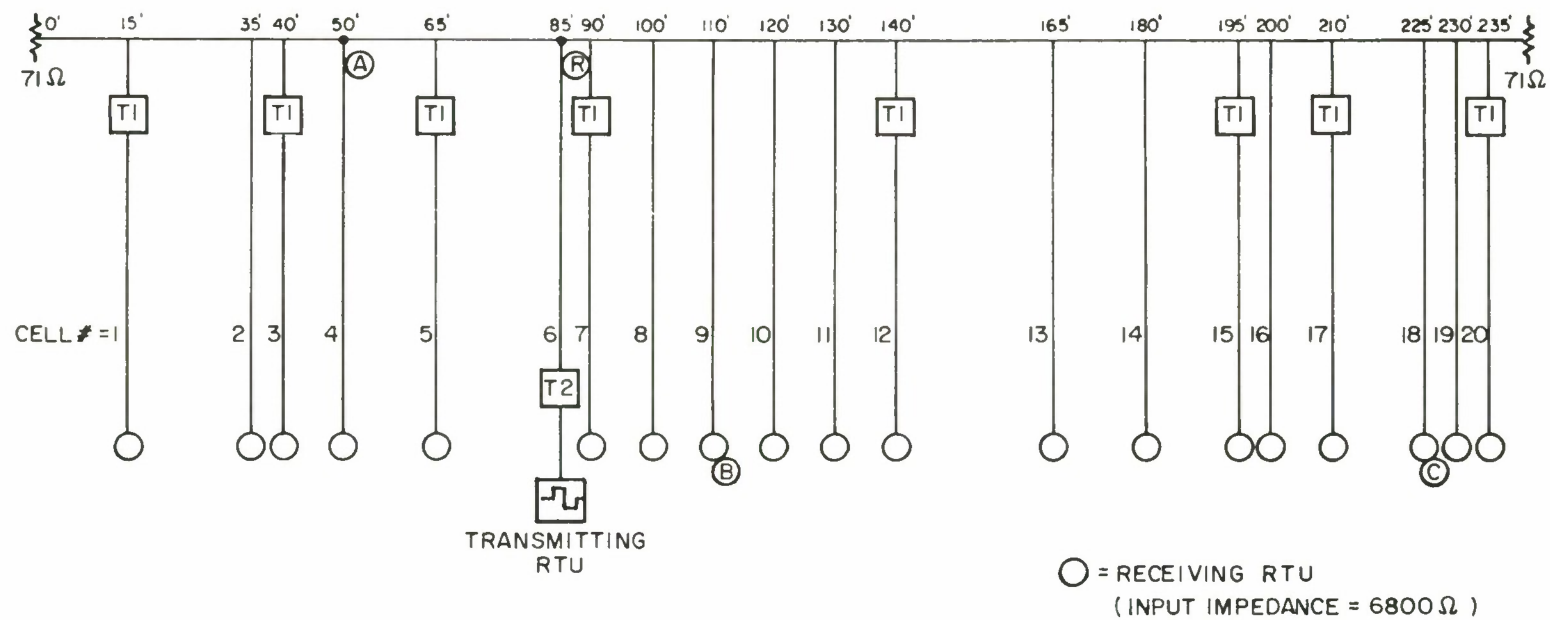


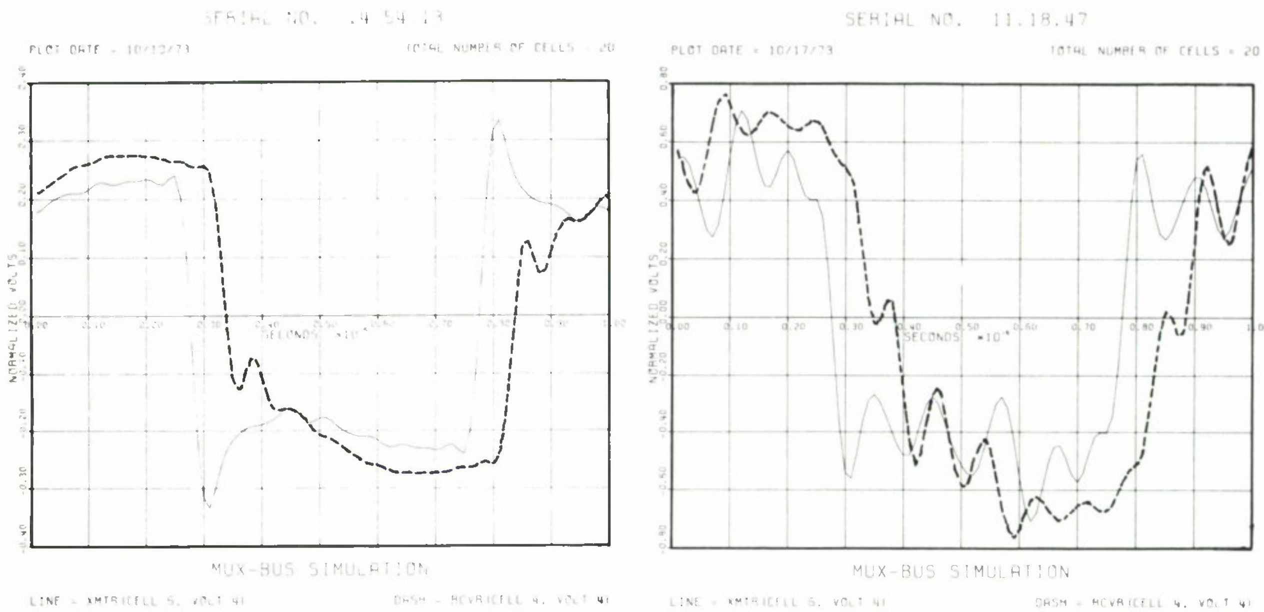
VOLTAGE MEASUREMENT POINTS:

Ⓐ = CELL 4 , VOLTAGE V(4)

Ⓑ = CELL 9 , VOLTAGE V(7)

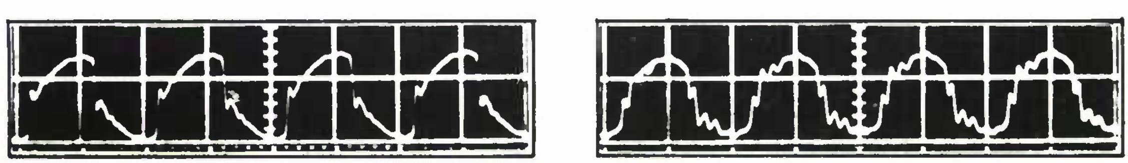
Ⓒ = CELL 18 , VOLTAGE V(7)

Figure 7 TWENTY CELL MULTIPLEX BUS



R1 = 56Ω
R2 = 0Ω

R1 = 0Ω
R2 = 0Ω



[WAVEFORMS MEASURED AT POINT "A" OF FIGURE 7]

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Figure 8 COMPARISON OF LABORATORY OSCILLOGRAPHS AND COMPUTER PLOTTED WAVEFORMS

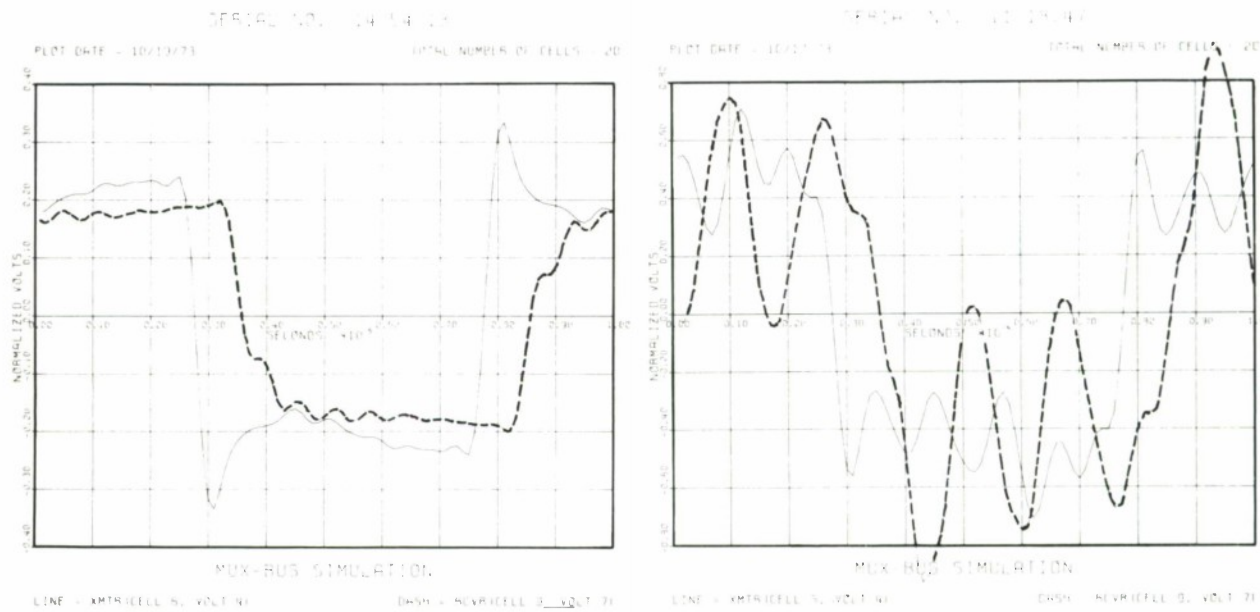
Since the degree of interaction is an inverse function of the driving point impedance of the stubs, the "smoothing" caused by the inclusion of resistances R1 is understandable.

CASE II. The second comparison to be discussed refers to the same bus architecture as CASE I, but considers the waveform at point "B" of Figure 7. The laboratory oscillographs and computer simulated waveforms with and without isolation resistances (R1) are shown in Figure 9. As in the previous case, good agreement between the oscillographs and the corresponding dashed waveforms on the computer plots empirically justifies the simulation algorithm. In addition, the set of waveforms for the R1 = 0 situation graphically displays the type of problem that can occur if a high degree of interaction is allowed between stubs. If a zero-crossing detector were used on this waveform, an erroneous output would probably occur if low pass filtering were not used. However, since the simulation can predict this potential problem the designer could employ filtering, isolation resistors, or a different type of detector to avoid this situation in an operational system.

CASE III. The final comparison to be made is shown in Figure 10. As in the previous cases, the bus architecture and transmitter location are unchanged. Here the point of observation has been moved to "C" in Figure 7. Good agreement is again shown but, more importantly, the simulation exhibits the same bandwidth limitation on a long bus that was found during the laboratory investigation.

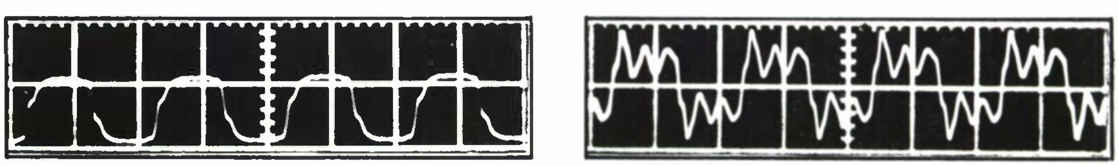
By considering the cases discussed above, along with many others not shown, a reasonable degree of confidence in the accuracy of the simulation was obtained. Hence, the next step in the investigation was to exercise the simulation beyond the scope of the laboratory effort in an attempt to expose possible problems or improvements in MIL-STD-1553. One of the early results of this study is shown in Figure 11.

The question addressed here was the effect, if any, on voltage waveforms caused by variation in the inductance of the cable used for the bus. A laboratory analysis of this question would be impractical, to say the least. However, as shown by the plotted waveforms in Figure 11, a possible problem area would be missed if this study were not done. In all four plots the dashed waveform is the simulated voltage at point "B" of Figure 7. Case II previously discussed this voltage waveform for a nominal cable inductance of 0.109 μh per foot. Plots "A" and "B" on the left of Figure 11 show the waveforms produced by varying the cable inductance $\pm$10% about its nominal value when isolation resistances R1 were installed in the bus of Figure 7. Comparing these two plots it is apparent that little sensitivity to an inductance variation of this magnitude



R1 = 56Ω
R2 = 0Ω

R1 = 0Ω
R2 = 0Ω



[WAVEFORMS MEASURED AT POINT "B" OF FIGURE 7]

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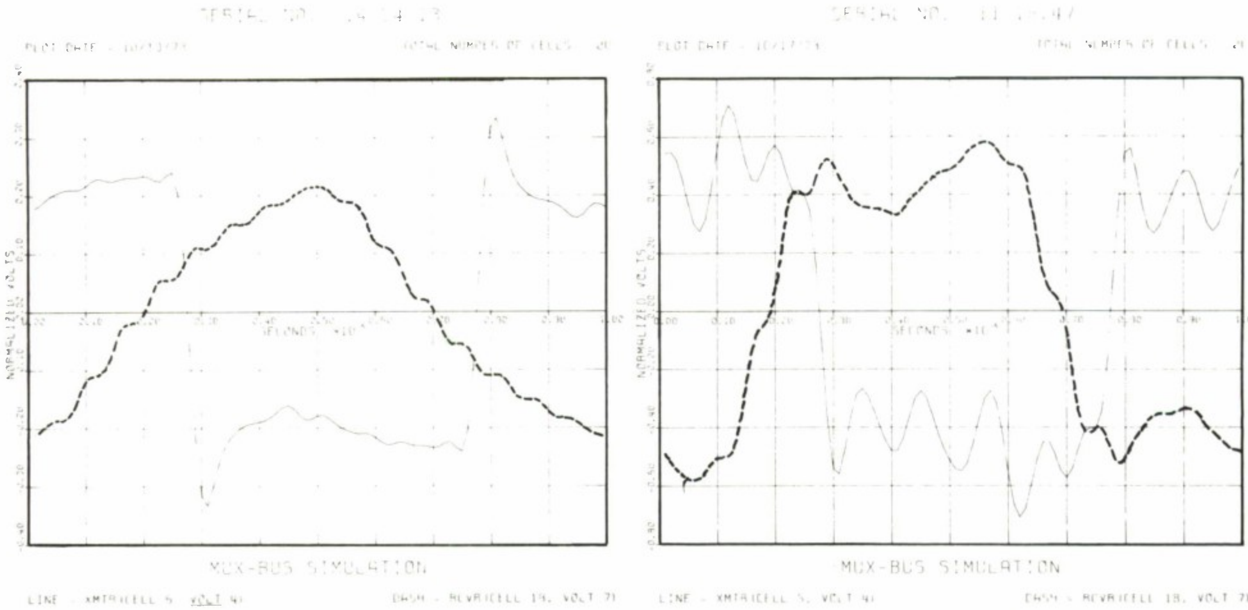
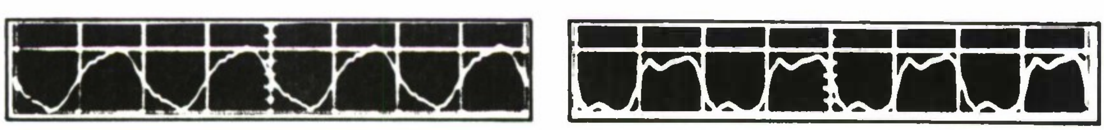
Figure 9 COMPARISON OF LABORATORY OSCILLOGRAPHS AND COMPUTER PLOTTED WAVEFORMS



R1 = 56 Ω
R2 = 0 Ω

R1 = 0 Ω
R2 = 0 Ω



[WAVEFORMS MEASURED AT POINT "C" OF FIGURE 7]

IA-45,190

Figure 10 COMPARISON OF LABORATORY OSCILLOGRAPHS AND COMPUTER PLOTTED WAVEFORMS

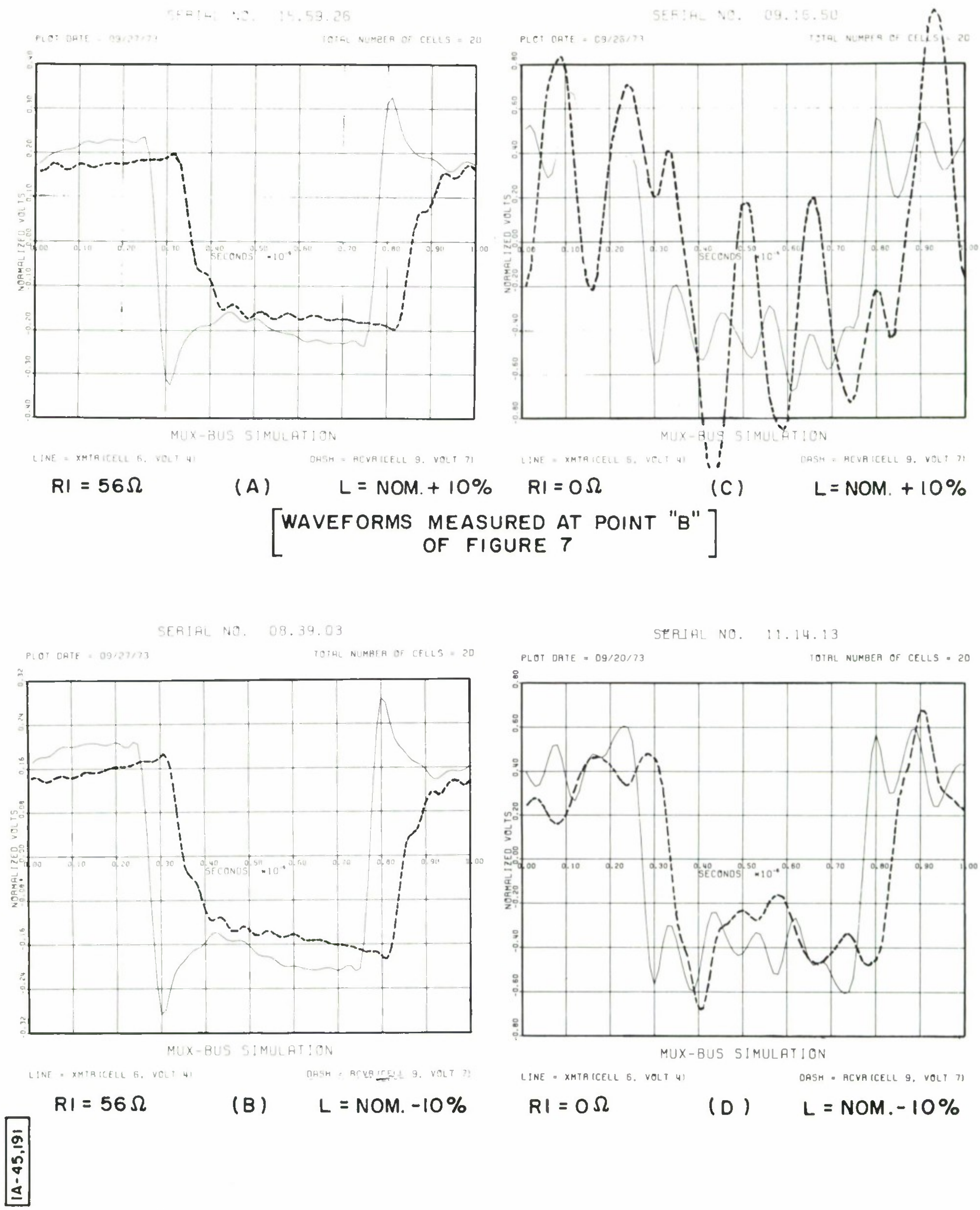


Figure 11 CABLE INDUCTANCE VARIATION ANALYSIS

would be expected. However, consider plots "C" and "D" on the right of Figure 11. Here a considerable change in waveform is displayed when resistors R1 are removed from the stubs and L is varied over the same $\pm 10\%$ range. Since cable manufacturing tolerances are within the range considered, it is entirely possible that a designer expecting waveform "D" might instead find waveform "C" when the bus was actually constructed, perhaps causing incompatibility with his detection circuitry. This inherent ability of computer simulation to permit variation of any system parameter by a simple change in software provides a powerful tool for analysis of multiplex bus systems.

APPENDIX I

SIMULATION SOFTWARE

In order to provide a better understanding of the simulation and to facilitate its use by interested parties, the following four topics will be addressed:

Part 1 - The computer system on which the simulation was exercised, including required capacities and peripheral equipment.

Part 2 - The basic simulation routine, called TPMOD2, with a discussion of required inputs and available outputs.

Part 3 - The plotting routine, PLMOD2, which produced the voltage waveform plots shown in Section IV.

Part 4 - The operational steps required to exercise the simulation on a computer installation similar to the author´s.

Part 1: Computer System Requirements - The simulation actually consists of two separate programs, TPMOD2 and PLMOD2. Both of these programs were written in FORTRAN IV and run on an IBM 370/155 computer. To exercise the programs without modification, the requirements of Table A1, Figure I.1 should be met. Table A2 lists the core and CPU demands found during a representative run made for a 32 stub MUX Bus.

Part 2: Description of TPMOD2 - In order to reduce computer core requirements and to increase flexability, the simulation was broken into two parts. The first part, called "TPMOD2", uses the architectural and component parameter inputs to produce a magnetic tape on which the complex voltage "phasors" for each harmonic at each node of Figure 1 are written. The operation of this program can best be explained by reference to the flow chart of Figure I.2 and the listing of the program immediately following.

TPMOD2 has essentially a three tiered structure. The first level, or main program, handles input and output, generation of the input voltage harmonic components, power calculations, and the sequencing of subroutine calls. Since this analysis is multivariate, involving both positions along the bus and frequency (harmonic), there are several nested loops in the sequencing portion of the routine. The harmonic number, or frequency, forms the outer loop inside of which the cell number, or position along the bus, is varied. As these parameters take on their allowed doublets, calls

COMPUTER SYSTEM REQUIREMENTS	
TO EXERCISE TPMOD2 WITHOUT MODIFICATION	TO EXERCISE PLMOD2 WITHOUT MODIFICATION
1) FORTRAN IV COMPILER 2) COMPLEX NOTATION & ARITHMETIC 3) 9-TRACK TAPE DRIVE	1) FORTRAN IV COMPILER 2) COMPLEX NOTATION & ARITHMETIC 3) 9-TRACK TAPE DRIVE 4) 7-TRACK TAPE DRIVE 5) CALCOMP PLOTTER AND SOFTWARE PACKAGE

TABLE A1

REPRESENTATIVE CORE REQUIREMENTS AND CPU TIMES FOR A 32 STUB MUX-BUS SIMULATION				
STEP	TPMOD2		PLMOD2 (13 PLOTS PRODUCED)	
	CPU	CORE	CPU	CORE
COMPILE	15S	120K	6S	104K
LINK/EDIT	2S	122K	2S	122K
RUN	7S	246K	11S	242K

TABLE A2

1A-45,078

Figure I.1 COMPUTER SYSTEM REQUIREMENTS

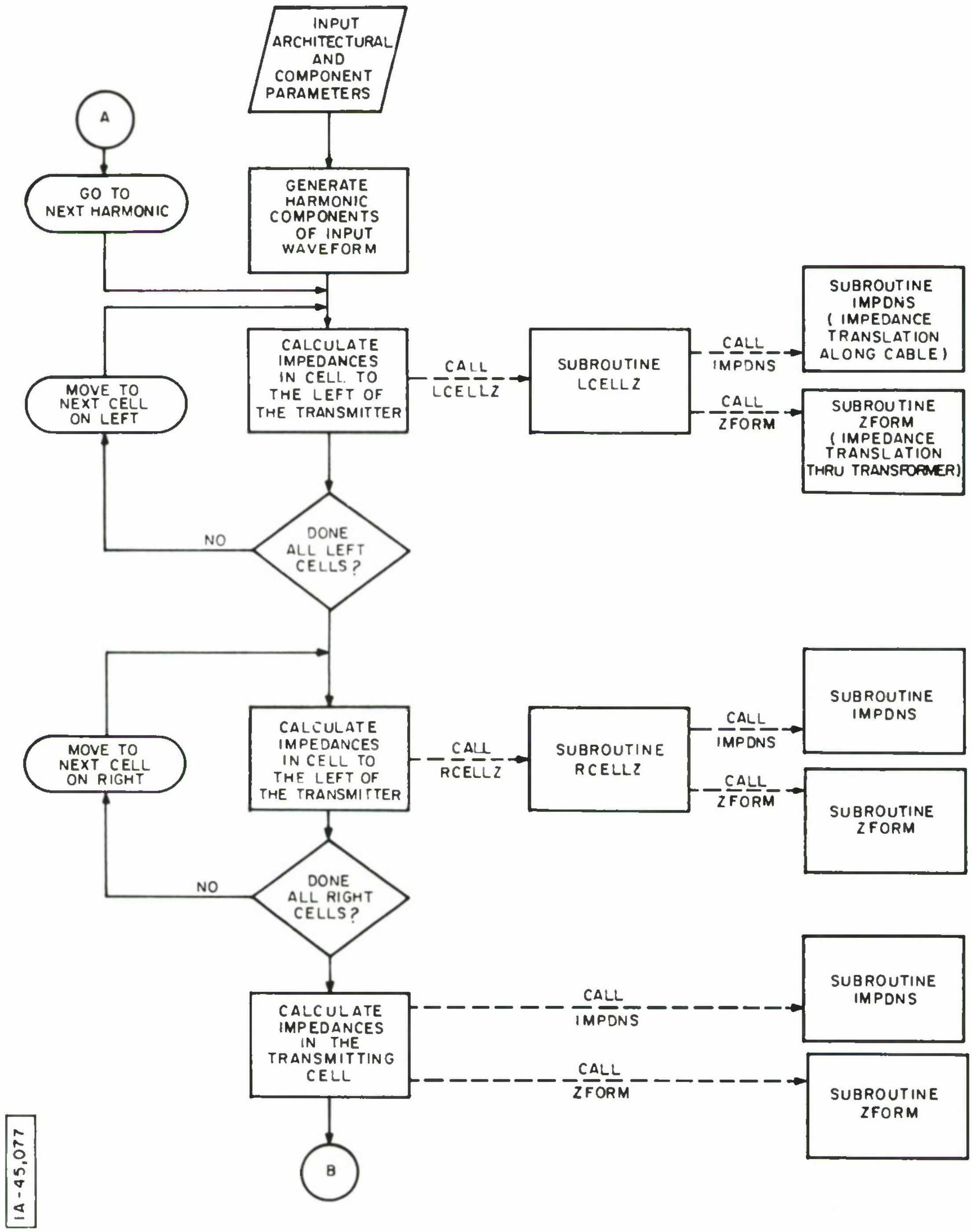


Figure I.2 FLOW CHART OF TPMOD2

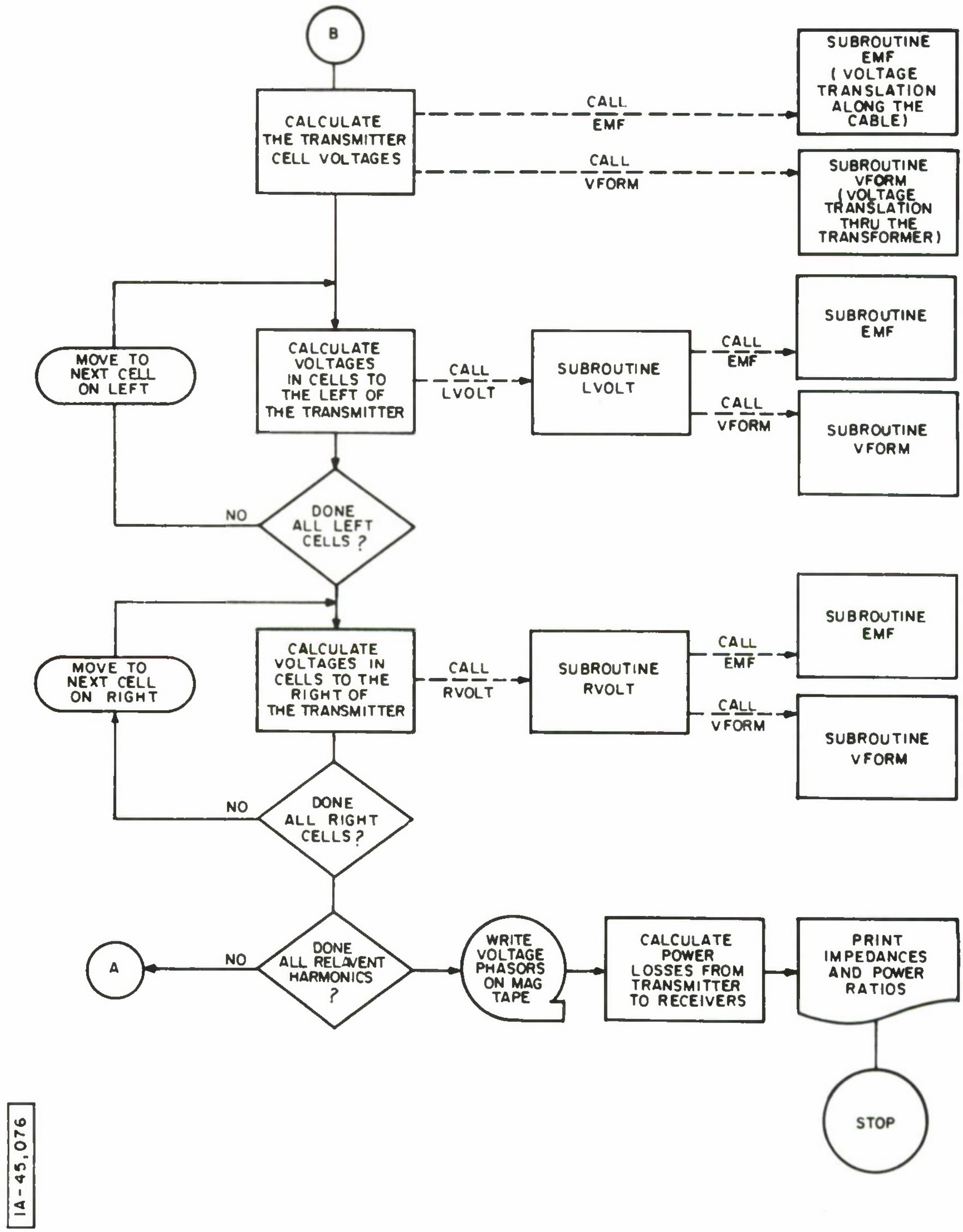


Figure 1.2 FLOW CHART OF TPMOD2 (CONT.)

```
              C      THIS PROGRAM DETERMINES VOLTAGE WAVEFORMS,
              C      DRIVING POINT IMPEDANCES AND POWER DISTRIBUTION
              C      FOR A MULTIPLEX BUS SYSTEM CONTAINING UP TO 32 STUBS
              C      WITH FLEXABILITY OF TRANSMITTER LOCATION
              C      AND TRANSFORMER PARAMETERS
              C
              C
              C      R=LINE SERIES RESISTANCE IN OHMS/UNIT LENGTH
              C      IND=LINE SERIES INDUCTANCE IN HENRIES/UNIT LENGTH
              C      G=LINE SHUNT CONDUCTANCE IN MHOS/UNIT LENGTH
              C      C=LINE SHUNT CAPACITANCE IN FARADS/UNIT LENGTH
              C      T=TRAPEZOIDAL WAVE PERIOD IN SECONDS
              C
              C
              C      TRANSFORMER PARAMETERS ARE REFERENCED TO SIDE OF TRANSFORMER
              C      CLOSEST TO BUS/STUB JUNCTION
              C
              C
              C      INPUT TRAPEZOIDAL WAVE HAS AMPLITUDE OF ONE
              C      WHEN FED INTO 75 OHM RESISTIVE LOAD.
              C
              C      IN E(K,M,N) *** K=HARMONIC ** L=VOLTAGE ** N=CELL ***
              C
              C
0001                 REAL LSTUB,MEX,IND,L1,LLAST,N1,N2
0002                 INTEGER XMTR,SERIAL,TXFMR,BXFMR
0003                 COMPLEX E,Z,FIN(30),ZSTUB,ZGEN,XMTRZ,PARLL,ZO,GAMMA,AMPED,Y,
                    1REFZ(30,6,32),ALPHSQ
0004                 DIMENSION RSTUB(32),LSTUB(32),SERIAL(2),
                    1XMTRPR(15),LBCELL(15),RCVRPR(15,32),RCVRTP(32)
0005                 COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
                    1TXFMR(32),BXFMR(32),PI
0006                 COMMON/IMPEMF/ZO,ALPHA,BETA
0007                 COMMON/TRANS/N1(5),N2(5),TR1(5),TR2(5),TL1(5),TL2(5),TLM(5),XMTR,T
              C
              C    INITIALIZATION:
              C
0008                 CALL CLOCK (SERIAL)
0009                 PI=3.14159265
0010                 READ(5,50)(N1(K),N2(K),TR1(K),TR2(K),TL1(K),TL2(K),TLM(K),K=1,2)
0011              50 FORMAT(4F5.2,3E10.4)
0012                 READ(5,100)R,IND,G,C,T,MAXHAR
0013             100 FORMAT(5E12.6,I3)
0014                 READ(5,101)TRISE,TFALL,PERCNT,ZGEN
0015             101 FORMAT(5E12.6)
0016                 READ(5,110)LAST,XMTR,RES1,L1,RLAST,LLAST
0017             110 FORMAT(2I2,4E10.4)
0018                 T1=TRISE
0019                 TO=(T-2.*T1)/2.
0020                 XOMEGA=2.*PI/T
0021                 XL=XOMEGA*IND
0022                 XC=XOMEGA*C
0023                 AMPEO=CMPLX(R,XL)
0024                 Y=CMPLX(G,XC)
0025                 ZO=CSQRT(AMPED/Y)
0026                 RO=REAL(ZO)
0027                 XO=AIMAG(ZO)
0028                 GAMMA=CSQRT(AMPED*Y)
```

LISTING OF TPMOD2

```
0029          ALPHA=REAL(GAMMA)
0030          BETA=AIMAG(GAMMA)
0031          DO 112 N=1,LAST
0032          READ(5,115)(R1(N),R2(N),RSTUB(N),LSTUB(N),L(1,N),L(2,N),L(3,N),
             1TXFMR(N),BXFMR(N))
0033      115 FORMAT(3F10.0,E10.4,5I5)
0034          TXFMR(N)=1
0035          RSTUB(N)=3730
0036      112 CONTINUE
        C
        C   WRITE THE INITIAL CONDITIONS:
        C
0037          WRITE(6,128)SERIAL
0038      128 FORMAT(40X,' ********** SERIAL NO. ',2A4,' **********',///)
0039          WRITE(6,130)
0040      130 FORMAT('0INPUT QUANTITIES:')
0041          WRITE(6,135)R,IND,G,C,T
0042      135 FORMAT('0    CABLE CHARACTERISTICS  R=',E12.6,' L=',E12.6,' G='
             1,E12.6,'  C=',E12.6,/,'      PULSE WIDTH=',F12.6)
0043          WRITE(6,137)TRISE,TFALL,PERCNT,ZGEN
0044      137 FORMAT('0    TRISE=',E12.6,'  TFALL=',E12.6,'  PERCENT CUTOFF=',
             1F5.2,'  GEN. IMPEDANCE=',E12.6,'+I(',E12.6,')')
0045          WRITE(6,140)R0,X0
0046      140 FORMAT('0    CHARACTERISTIC IMPEDANCE = ',E14.8,' +I(',E14.8,')')
0047          WRITE(6,145)LAST,XMTR
0048      145 FORMAT('0    NUMBER OF CELLS=',I3,'    XMTR IN CELL',I3)
0049          WRITE(6,147)RES1,L1
0050      147 FORMAT('0    LEFT TERMINATION RES.=',E10.4,
             1'    LEFT TERMINATION IND.=',E10.4)
0051          WRITE(5,148)RLAST,LLAST
0052      148 FORMAT('0    RIGHT TERMINATION RES.=',E10.4,
             1'    RIGHT TERMINATION IND.=',E10.4)
0053          WRITE(6,153)(K,N1(K),N2(K),TR1(K),TR2(K),TL1(K),TL2(K),
             1TLM(K),K=1,2)
0054      153 FORMAT('0    IN TRANSFORMER ',I2,',N1=',F5.2,'  N2=',F5.2,
             1'  R1=',F5.2,'  R2=',F5.2,'  L1=',E10.4,'  L2=',F10.4,
             3'  LM=',E10.4)
0055          DO 165 N=1,LAST
0056          WRITE(6,155)N
0057      155 FORMAT('-    IN CELL',I3)
0058          WRITE(6,160)L(1,N),L(2,N),L(3,N),LSTUB(N),R1(N),R2(N),RSTUB(N)
             1,TXFMR(N),BXFMR(N)
0059      160 FORMAT('     L(1,N)=',I3,2X,'L(2,N)=',I3,2X,'L(3,N)=',I3,2X,
             1'LSTUB(N)=',E10.4,2X,'R1(N)=',F6.0,2X,'R2(N)=',F6.0,2X,'RSTUB(N)='
             2,F6.0,2X,'TXFMR=',I2,2X,'BXFMR=',I2)
0060      165 CONTINUE
        C
        C   CALCULATE VALUES FOR EIN:
        C
0061          CUTOFF=0.0
0062          DO 1 J=1,MAXHAR,1
0063          AJ=J+(J-1)
0064          EXN=2.*SIN(PI*AJ*TI/T)*SIN(PI*AJ*(T0+TI)/T)
0065          EXD=PI*AJ*TI/T*PI*AJ*(T0+TI)/T
0066          EX=2.*EXN/EXD
0067          MEX=EX**2
0068          NN=J
0069          EIN(J)=CMPLX(EX,0.0)
```

LISTING OF TPMOD2 (Con't)

```
0070             IF(MEX.LE.CUTOFF)GO TO 195
0071             IF(J.GT.1)GO TO 1
0072             CUTOFF=(EX**2)*PERCNT/100.
0073           1 CONTINUE
0074         195 CONTINUE
0075             N=2*NN-1
0076             WRITE(6,185)NN
0077         185 FORMAT('0    NUMBER OF HARMONICS CONSIDERED=',I4)
0078             WRITE(6,187)N
0079         187 FORMAT('0    HIGHEST HARMONIC=',I4)
0080             WRITE(6,128)SERIAL
0081             WRITE(6,900)XMTR
0082         900 FORMAT(1H1,//,10X,'DRIVING POINT IMPEDANCE AT XMTR/STUB JUNCTION',
                1' .VS. FREQUENCY',/,26X,' XMTR IS IN CELL ',I3,//,17X,'HERTZ'
                2,15X,' OHMS',30X,'MAGNITUDE',14X,'ANGLE')
           C
           C     COMPUTE IMPEDANCES AND VOLTAGES AT EACH HARMONIC
           C
0083             DO 2 K=1,NN
0084             Q=2.*K-1.
0085             XL1=XL*Q
0086             XC1=XC*Q
0087             AMPED=CMPLX(R,XL1)
0088             Y=CMPLX(G,XC1)
0089             ZO=CSQRT(AMPED/Y)
0090             GAMMA=CSQRT(AMPED*Y)
0091             ALPHA=REAL(GAMMA)
0092             BETA=AIMAG(GAMMA)
           C
           C     COMPUTE STUB IMPEDANCES
           C
0093             DO 4 N=1,LAST
0094             XLSTUB=XOMEGA*Q*LSTUB(N)
0095             ZSTUB(K,N)=CMPLX(RSTUB(N),XLSTUB)
0096           4 Z(K,7,N)=ZSTUB(K,N)
           C
           C     COMPUTE TERMINATION IMPEDANCES
           C
0097             XL1=XOMEGA*Q*L1
0098             Z(K,1,1)=CMPLX(RES1,XL1)
0099             XLLAST=XOMEGA*Q*LLAST
0100             Z(K,2,LAST)=CMPLX(RLAST,XLLAST)
           C
           C     GENERATE LEFT CELL IMPEDANCES
           C
0101             N=1
0102             IF(N.EQ.XMTR)GO TO 12
0103          10 CONTINUE
0104             CALL LCELLZ(K,N)
0105             N=N+1
0106             IF(N.LT.XMTR)GO TO 10
           C
           C     GENERATE RIGHT CELL IMPEDANCES
           C
0107          12 CONTINUE
0108             N=LAST
0109             IF(N.EQ.XMTR)GO TO 17
0110          15 CONTINUE
```

LISTING OF TPMOD2 (Con't)

```
0111                CALL RCELLZ(K,N,LAST)
0112                N=N-1
0113                IF(N.GT.XMTR)GO TO 15
0114             17 CONTINUE
              C
              C     GENERATE XMTR CELL IMPEDANCES
              C
0115                N=XMTR
0116                IF(N.EQ.1)GO TO 20
0117                Z(K,1,N)=Z(K,2,N-1)
0118             20 CONTINUE
0119                IF(N.EQ.LAST)GO TO 25
0120                Z(K,2,N)=Z(K,1,N+1)
0121             25 CONTINUE
0122                CALL IMPDNS(Z(K,1,N),L(1,N),Z(K,4,N))
0123                CALL IMPDNS(Z(K,2,N),L(2,N),Z(K,5,N))
0124                Z(K,6,N)=Z(K,4,N)*Z(K,5,N)/(Z(K,4,N)+Z(K,5,N))+2.*R1(N)
0125                Z(K,8,N)=Z(K,6,N)
              C
              C     REFZ IS THE IMPEDANCE AT THE BUS/STUB JUNCTION
              C
0126                REFZ(K,6,N)=Z(K,6,N)-2.*R1(N)
0127                IF(TXFMR(N).LT.1)GO TO 26
              C
              C     CALL THE IMPEDANCE XFMR SUBROUTINE
              C     LSET=1 MEANS USE TOP XFMR PARAMETERS
              C     LSET=2 MEANS USE BOTTOM XFMR PARAMETERS
              C
0128                M=3
0129                LSET=1
0130                CALL ZFORM(K,M,N,LSET)
0131             26 CONTINUE
0132                CALL IMPDNS(Z(K,8,N),L(3,N),Z(K,3,N))
0133                Z(K,9,N)=Z(K,3,N)
0134                IF(BXFMR(N).LT.1)GO TO 27
              C
              C     CALL THE IMPEDANCE XFMR SUBROUTINE
              C
0135                M=9
0136                LSET=2
0137                CALL ZFORM(K,M,N,LSET)
0138             27 CONTINUE
0139                XMTRZ=Z(K,9,N)+2.*R2(N)
0140                Z(K,7,XMTR)=XMTRZ
0141                RETRZ=REAL(XMTRZ)
0142                CXTRZ=AIMAG(XMTRZ)
0143                SIZE=SQRT(RETRZ**2+CXTRZ**2)
0144                XMTNG=(ATAN2(CXTRZ,RETRZ))/PI*180.
0145                FRQ=(2*K-1)*1./T
0146                WRITE(6,901)FRQ,RETRZ,CXTRZ,SIZE,XMTNG
0147            901 FORMAT(/,16X,F8.3,6X,F8.2,1X,'+J(',F8.2,')',
                   120X,F8.2,15X,F7.2)
              C
              C
              C     GENERATE XMTR CELL VOLTAGES
              C
0148                N=XMTR
0149                E(K,7,N)=EIN(K)*XMTRZ/(XMTRZ+ZGEN)
```

LISTING OF TPMOD2 (Con't)

```
      E(K,9,N)=E(K,7,N)*Z(K,9,N)/(Z(K,9,N)+2.*R2(N))
      E(K,3,N)=E(K,9,N)
      IF(BXFMR(N).LT.1)GO TO 28
C
C     CALL THE VOLTAGE XFMR SUBROUTINE
C
      M=3
      LSET=2
      CALL VFORM(K,M,N,LSET)
C
   28 CONTINUE
      CALL EMF(E(K,3,N),Z(K,3,N),L(3,N),E(K,8,N))
      E(K,6,N)=E(K,8,N)
      IF(TXFMR(N).LT.1)GO TO 29
C
C     CALL THE VOLTAGE XFMR SUBROUTINE
C
      M=6
      LSET=1
      CALL VFORM(K,M,N,LSET)
C
   29 CONTINUE
      PARLL=Z(K,4,N)*Z(K,5,N)/(Z(K,4,N)+Z(K,5,N))
      E(K,4,N)=E(K,6,N)*PARLL/(PARLL+2.*R1(N))
      E(K,5,N)=E(K,4,N)
      CALL EMF(E(K,4,N),Z(K,4,N),L(1,N),E(K,1,N))
      CALL EMF(E(K,5,N),Z(K,5,N),L(2,N),E(K,2,N))
C
C     GENERATE LEFT CELL VOLTAGES
C
      IF(XMTR.EQ.1)GO TO 35
      N=XMTR-1
   30 CONTINUE
      CALL LVOLT(K,N)
      N=N-1
      IF(N.GE.1)GO TO 30
   35 CONTINUE
C
C     GENERATE RIGHT CELL VOLTAGES
C
      IF(XMTR.EQ.LAST)GO TO 45
      N=XMTR+1
   40 CONTINUE
      CALL RVOLT(K,N)
      N=N+1
      IF(N.LE.LAST)GO TO 40
   45 CONTINUE
    2 CONTINUE
C
C     WRITE COMPLEX PHASOR VALUES ON MAG TAPE
C
      WRITE(11)SERIAL,LAST,XMTR,T,NN
      WRITE(11)(((E(K,M,N),K=1,NN,1),M=1,9,1),N=1,LAST,1)
C
C     DETACHED STUB IMPEDANCE
C
      N=1
      IF(N.EQ.XMTR) N=2
```

LISTING OF TPMOD2 (Con't)

```
0188          947 CONTINUE
0189              WRITE(6,128)SERIAL
0190              WRITE(6,905)N
0191          905 FORMAT(1H1,//,10X,'DRIVING POINT IMPEDANCE OF STUB ',I2,
                 1' .VS. FREQUENCY',//,17X,'HERTZ',15X,' OHMS',
                 230X,'MAGNITUDE',14X,'ANGLE')
0192              M=6
0193              DO 950 K=1,NN,1
0194              FRQ=(2*K-1)*1./T
0195              REZ=REAL(Z(K,M,N))+2.*R1(N)
0196              CXZ=AIMAG(Z(K,M,N))
0197              SIZE=SQRT(REZ**2+CXZ**2)
0198              STUBNG=(ATAN2(CXZ,REZ))/PI*180.
0199              WRITE(6,906)FRQ,REZ,CXZ,SIZE,STUBNG
0200          906 FORMAT(/,15X,E8.3,6X,F8.2,1X,'+J(',F8.2,')',
                 120X,F8.2,15X,F7.2)
0201          950 CONTINUE
            C
            C     GENERATE THE AVERAGE XMTR POWER .VS. FREQUENCY
            C
0202              TXMTRP=0.0
0203              DO 955 K=1,NN
0204              XMTRZ=Z(K,7,XMTR)
0205              CONST=(CABS(E(K,7,XMTR))**2)/(2.*CABS(XMTRZ))
0206              REZ=REAL(XMTRZ)
0207              CXZ=AIMAG(XMTRZ)
0208              ANG=ATAN2(CXZ,REZ)
0209              XMTRPR(K)=CONST*COS(ANG)
0210              TXMTRP=TXMTRP+XMTRPR(K)
0211          955 CONTINUE
            C
            C     NODE DRIVING POINT IMPEDANCE
            C
0212              N=0
0213          960 CONTINUE
0214              TOTPWR=0.0
0215              N=N+1
0216              WRITE(6,128)SERIAL
0217              WRITE(6,907)N
0218          907 FORMAT(1H1,//,10X,'NODE DRIVING POINT IMPEDANCE .VS. FREQUENCY',
                 1' FOR CELL ',I2,/,17X,'HERTZ',15X,' OHMS',
                 220X,'MAGNITUDE',10X,'ANGLE',13X,'POWER RATIO(DB)')
0219              M=6
0220              IF(N.LT.XMTR) M=5
0221              IF(N.GT.XMTR) M=4
0222              K=0
0223          980 CONTINUE
0224              HARPWR=0.0
0225              K=K+1
0226              F=(2*K-1)*1./T
0227              IF(N.EQ.XMTR)Z(K,M,N)=REFZ(K,M,N)
0228              REZ=REAL(Z(K,M,N))
0229              CXZ=AIMAG(Z(K,M,N))
0230              SIZE=SQRT(REZ**2+CXZ**2)
0231              ANONG=(ATAN2(CXZ,REZ))/PI*180.
            C
            C     GENERATE POWER RATIOS(DB) AT NODES
            C
```

LISTING OF TPMOD2 (Con't)

```
      IF(N.EQ.XMTR) E(K,M,N)=E(K,4,N)
      CONST=(CABS(E(K,M,N))**2)/(2.*CABS(Z(K,M,N)))
      ANG=ATAN2(CXZ,REZ)
      HARPWR=CONST*COS(ANG)
      RAT=HARPWR/XMTRPR(K)
      PWRRAT=10.*ALOG10(RAT)
      TOTPWR=TOTPWR+HARPWR
      WRITE(6,910)F,REZ,CXZ,SIZE,ANDNG,PWRRAT
  910 FORMAT(/,16X,F8.3,6X,F8.2,1X,'+J(',F8.2,')',
     110X,F8.2,10X,F7.2,16X,F7.2)
      IF(K.LT.NN) GO TO 980
      RAT=TOTPWR/TXMTRP
      TOTRAT=10.*ALOG10(RAT)
      WRITE(6,915)TOTRAT
  915 FORMAT(////,10X,'POWER RATIO=(POWER AT THIS NODE)/(REFERENCE POWER
     1) IN DB',/,15X,'THE REFERENCE POWER IS THE XMTR OUTPUT POWER.',
     2//,10X,'TOTAL POWER RATIO(DB)=',F8.2)
      IF(N.LT.LAST) GU TU 960
      WRITE(6,128)SERIAL
C
C     GENERATE POWER RATIOS AT THE RECEIVERS
C
      DO 961 K=1,NN
      LBCELL(K)=2*K-1
  961 CONTINUE
      M=7
      DO 965 N=1,LAST
      IF(N.EQ.XMTR) GO TO 965
      RCVRTP(N)=0.0
      DO 970 K=1,NN
      CONST=(CABS(E(K,M,N))**2)/(2.*CABS(ZSTUB(K,N)))
      REZ=REAL(ZSTUB(K,N))
      CXZ=AIMAG(ZSTUB(K,N))
      ANG=ATAN2(CXZ,REZ)
      HARPWR=CONST*COS(ANG)
      RAT=HARPWR/XMTRPR(K)
      RCVRPR(K,N)=10.*ALOG10(RAT)
      RCVRTP(N)=RCVRTP(N)+HARPWR
  970 CONTINUE
      RAT=RCVRTP(N)/TXMTRP
      RCVRTP(N)=10.*ALOG10(RAT)
  965 CONTINUE
      WRITE(6,975)(LBCELL(K),K=1,NN)
  975 FORMAT(1H1,///,40X,'POWER RATIO AT RECEIVERS (DB)',//,49X,
     1'** HARMONIC **',/,24X,'COMBINED',6X,10(I2,7X))
      WRITE(6,977)
  977 FORMAT(/,10X,'**RECEIVER**')
      DO 981 N=1,LAST
      IF(N.EQ.XMTR) GO TO 981
      WRITE(6,990)(N,RCVRTP(N),(RCVRPR(K,N),K=1,NN))
  990 FORMAT(15X,I2,6X,F7.2,5X,10(F7.2,2X))
  981 CONTINUE
      WRITE(6,995)
  995 FORMAT(////,10X,'POWER RATIO=(RECEIVER POWER/XWTR OUTPUT POWER) IN
     1 DB.',//)
      WRITE(6,128)SERIAL
      STOP
      END
```

LISTING OF TPMOD2 (Con't)

```
FORTRAN IV G LEVEL  21                MAIN              DATE = 74281         09/52/49             PAGE 0001

                C
                C
                C
                C
 0001                  SUBROUTINE LCELLZ (K,N)
 0002                  COMPLEX Z,ZSTUB,E,PARLL
 0003                  INTEGER BXFMR,TXFMR
 0004                  COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
                      1TXFMR(32),BXFMR(32),PI
 0005                  IF(N.EQ.1)GO TO 1000
 0006                  Z(K,1,N)=Z(K,2,N-1)
 0007             1000 CONTINUE
 0008                  CALL IMPDNS(Z(K,1,N),L(1,N),Z(K,4,N))
 0009                  Z(K,3,N)=ZSTUB(K,N)+2.*R2(N)
 0010                  Z(K,9,N)=Z(K,3,N)
 0011                  IF(BXFMR(N).LT.1)GO TO 100
                C
                C      CALL THE TRANSFORMER SUBROUTINE
                C      LSET=1 MEANS USE TOP XFMR PARAMETERS
                C      LSET=2 MEANS USE BOTTOM XFMR PARAMETERS
                C
 0012                  M=3
 0013                  LSET=2
 0014                  CALL ZFORM(K,M,N,LSET)
 0015              100 CONTINUE
 0016                  CALL IMPDNS(Z(K,3,N),L(3,N),Z(K,6,N))
 0017                  Z(K,8,N)=Z(K,6,N)
 0018                  IF(TXFMR(N).LT.1)GO TO 200
                C
                C      CALL THE TRANSFORMER SUBROUTINE
                C
 0019                  M=6
 0020                  LSET=1
 0021                  CALL ZFORM(K,M,N,LSET)
 0022              200 CONTINUE
 0023                  PARLL=Z(K,6,N)+2.*R1(N)
 0024                  Z(K,5,N)=Z(K,4,N)*PARLL/(Z(K,4,N)+PARLL)
 0025                  CALL IMPDNS(Z(K,5,N),L(2,N),Z(K,2,N))
 0026                  RETURN
 0027                  END
```

LISTING OF SUBROUTINE LCELL Z

```
FORTRAN IV G LEVEL  21                MAIN              DATE = 74281          09/52/49              PAGE 0001

                C
                C
 0001                 SUBROUTINE RCELLZ (K,N,LAST)
 0002                 COMPLEX Z,ZSTUB,E,PARLL
 0003                 INTEGER BXFMR,TXFMR
 0004                 COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
                     1TXFMR(32),BXFMR(32),PI
 0005                 IF(N.EQ.LAST)GO TO 2000
 0006                 Z(K,2,N)=Z(K,1,N+1)
 0007            2000 CONTINUE
 0008                 CALL IMPDNS(Z(K,2,N),L(2,N),Z(K,5,N))
 0009                 Z(K,3,N)=ZSTUB(K,N)+2.*R2(N)
 0010                 Z(K,9,N)=Z(K,3,N)
 0011                 IF(BXFMR(N).LT.1)GO TO 100
                C
                C     CALL THE TRANSFORMER SUBROUTINE
                C     LSET=1 MEANS USE TOP XFMR PARAMETERS
                C     LSET=2 MEANS USE BOTTOM XFMR PARAMETERS
                C
 0012                 M=3
 0013                 LSET=2
 0014                 CALL ZFORM(K,M,N,LSET)
 0015             100 CONTINUE
 0016                 CALL IMPDNS(Z(K,3,N),L(3,N),Z(K,6,N))
 0017                 Z(K,8,N)=Z(K,6,N)
 0018                 IF(TXFMR(N).LT.1)GO TO 200
                C
                C     CALL THE TRANSFORMER SUBROUTINE
                C
 0019                 M=6
 0020                 LSET=1
 0021                 CALL ZFORM(K,M,N,LSET)
 0022             200 CONTINUE
 0023                 PARLL=Z(K,6,N)+2.*R1(N)
 0024                 Z(K,4,N)=Z(K,5,N)*PARLL/(Z(K,5,N)+PARLL)
 0025                 CALL IMPDNS(Z(K,4,N),L(1,N),Z(K,1,N))
 0026                 RETURN
 0027                 END
```

LISTING OF SUBROUTINE RCELL Z

```
               C
               C
0001                  SUBROUTINE LVOLT (K,N)
0002                  COMPLEX E,Z,ZSTUB,ALPHSQ
0003                  INTEGER BXFMR,TXFMR
0004                  REAL N1,N2
0005                  COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
                     1TXFMR(32),BXFMR(32),PI
0006                  COMMON/TRANS/N1(5),N2(5),TR1(5),TR2(5),TL1(5),TL2(5),TLM(5),XMTR,T
0007                  E(K,2,N)=E(K,1,N+1)
0008                  CALL EMF(E(K,2,N),Z(K,2,N),L(2,N),E(K,5,N))
0009                  E(K,4,N)=E(K,5,N)
0010                  CALL EMF(E(K,4,N),Z(K,4,N),L(1,N),E(K,1,N))
0011                  E(K,6,N)=E(K,5,N)*Z(K,6,N)/(Z(K,6,N)+2.*R1(N))
0012                  E(K,8,N)=E(K,6,N)
0013                  IF(TXFMR(N).LT.1)GO TO 10
               C
               C      CALL THE VOLTAGE XFMR SUBROUTINE
               C
0014                  M=8
0015                  LSET=1
0016                  CALL VFORM(K,M,N,LSET)
0017               10 CONTINUE
0018                  CALL EMF(E(K,8,N),Z(K,8,N),L(3,N),E(K,3,N))
0019                  E(K,9,N)=E(K,3,N)
0020                  IF(BXFMR(N).LT.1)GO TO 20
               C
               C      CALL THE VOLTAGE XFMR SUBROUTINE
               C
0021                  M=9
0022                  LSET=2
0023                  CALL VFORM(K,M,N,LSET)
0024               20 CONTINUE
0025                  E(K,7,N)=E(K,9,N)*ZSTUB(K,N)/(ZSTUB(K,N)+2.*R2(N))
0026                  RETURN
0027                  END
```

LISTING OF SUBROUTINE LVOLT

```
C
C
      SUBROUTINE RVOLT (K,N)
      COMPLEX E,Z,ZSTUB,ALPHSQ
      INTEGER BXFMR,TXFMR
      REAL N1,N2
      COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
     1TXFMR(32),BXFMR(32),PI
      COMMON/TRANS/N1(5),N2(5),TR1(5),TR2(5),TL1(5),TL2(5),TLM(5),XMTR,T
      E(K,1,N)=E(K,2,N-1)
      CALL EMF(E(K,1,N),Z(K,1,N),L(1,N),E(K,4,N))
      E(K,5,N)=E(K,4,N)
      CALL EMF(E(K,5,N),Z(K,5,N),L(2,N),E(K,2,N))
      E(K,6,N)=E(K,4,N)*Z(K,6,N)/(Z(K,6,N)+2.*R1(N))
      E(K,8,N)=E(K,6,N)
      IF(TXFMR(N).LT.1)GO TO 10
C
C     CALL THE VOLTAGE XFMR SUBROUTINE
C
      M=8
      LSET=1
      CALL VFORM(K,M,N,LSET)
   10 CONTINUE
      CALL EMF(E(K,8,N),Z(K,3,N),L(3,N),E(K,3,N))
      E(K,9,N)=E(K,3,N)
      IF(BXFMR(N).LT.1)GO TO 20
C
C     CALL THE VOLTAGE XFMR SUBROUTINE
C
      M=9
      LSET=2
      CALL VFORM(K,M,N,LSET)
   20 CONTINUE
      E(K,7,N)=E(K,9,N)*ZSTUB(K,N)/(ZSTUB(K,N)+2.*R2(N))
      RETURN
      END
```

LISTING OF SUBROUTINE RVOLT

```
FORTRAN IV G LEVEL  21                  MAIN              DATE = 74281         09/52/49                PAGE 0001

C
C
      SUBROUTINE ZFORM(K,M,N,LSET)
      COMPLEX Z,ZSTUB,E,PARLL,ALPHSQ,REACL1,REACL2,REACLM
      INTEGER R,XMTR
      REAL N1,N2
      COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
     1TXFMR(32),BXFMR(32),PI
      COMMON/TRANS/N1(5),N2(5),TR1(5),TR2(5),TL1(5),TL2(5),TLM(5),XMTR,T
      R=LSET
      ATURNS=(N1(R)/N2(R))**2
      ALPHSQ=CMPLX(ATURNS,0.0)
      Q=2.*K-1.
      XOMEGA=2.*3.14159265/T
      CONST=Q*XOMEGA*TL1(R)
      REACL1=CMPLX(TR1(R),CONST)
      CONST=Q*XOMEGA*TL2(R)
      REACL2=CMPLX(TR2(R),CONST)
      CONST=Q*XOMEGA*TLM(R)
      REACLM=CMPLX(0.0,CONST)
      IF(N.EQ.XMTR)GO TO 200
      PARLL=ALPHSQ*(Z(K,M,N)+REACL2)
      Z(K,M,N)=(PARLL*REACLM)/(PARLL+REACLM)+REACL1
      GO TO 300
  200 CONTINUE
      ATURNS=(N2(R)/N1(R))**2
      ALPHSQ=CMPLX(ATURNS,0.0)
      PARLL=ALPHSQ*(Z(K,M,N)+REACL1)
      Z(K,M,N)=(PARLL*(ALPHSQ*REACLM))/(PARLL+ALPHSQ*REACLM)+REACL2
  300 CONTINUE
      RETURN
      END
```

LISTING OF SUBROUTINE ZFORM

```
FORTRAN IV G LEVEL  21                MAIN              DATE = 74281        09/52/49              PAGE 0001

              C
              C
                    SUBROUTINE VFORM(K,M,N,LSET)
                    COMPLEX Z,ZSTUB,E,ALPHA,ALPHSQ,REACL1,REACL2,REACLM,DUMMY
                    INTEGER R,XMTR
                    REAL N1,N2
                    COMMON Z(30,9,32),ZSTUB(30,32),E(30,9,32),L(3,32),R1(32),R2(32),
                   1TXFMR(32),BXFMR(32),PI
                    COMMON/TRANS/N1(5),N2(5),TR1(5),TR2(5),TL1(5),TL2(5),TLM(5),XMTR,T
                    R=LSET
                    TURNS=N1(R)/N2(R)
                    ALPHA=CMPLX(TURNS,0.0)
                    ALPHSQ=ALPHA*ALPHA
                    Q=2.*K-1.
                    XOMEGA=2.*PI/T
                    CONST=Q*XOMEGA*TL1(R)
                    REACL1=CMPLX(TR1(R),CONST)
                    CONST=Q*XOMEGA*TL2(R)
                    REACL2=CMPLX(TR2(R),CONST)
                    CONST=Q*XOMEGA*TLM(R)
                    REACLM=CMPLX(0.0,CONST)
                    IF(N.EQ.XMTR)GO TO 200
                    DUMMY=(ALPHSQ)*(Z(K,M,N)+REACL2)
                    DUMMY=REACLM*DUMMY/(REACLM+DUMMY)
                    E(K,M,N)=E(K,M,N)*DUMMY/(DUMMY+REACL1)
                    E(K,M,N)=E(K,M,N)*Z(K,M,N)/(REACL2+Z(K,M,N))
                    E(K,M,N)=E(K,M,N)/ALPHA
                    GO TO 300
                200 CONTINUE
                    DUMMY=(Z(K,M,N)+REACL1)/ALPHSQ
                    DUMMY=DUMMY*(REACLM/ALPHSQ)/(DUMMY+REACLM/ALPHSQ)
                    E(K,M,N)=E(K,M,N)*(DUMMY/(DUMMY+REACL2))
                    E(K,M,N)=E(K,M,N)*Z(K,M,N)/(Z(K,M,N)+REACL1)
                    E(K,M,N)=E(K,M,N)*ALPHA
                300 CONTINUE
                    RETURN
                    END
```

LISTING OF SUBROUTINE VFORM

```
FORTRAN IV G LEVEL  21                MAIN             DATE = 74281          09/52/49            PAGE 0001

            C
            C
                  SUBROUTINE IMPDNS (ZL,L,ZS)
                  COMPLEX ZZ,ZL,ZS,A,B,NUM,DENOM
                  COMMON/IMPEMF/ZZ,ALPHA,BETA
                  E=ALPHA*L
                  F=BETA*L
                  A=ZZ*ZL*COSH(E)*COS(F)+ZZ*ZZ*SINH(E)*COS(F)
                  B=ZZ*ZL*SINH(E)*SIN(F)+ZZ*ZZ*COSH(E)*SIN(F)
                  C=REAL(A)-AIMAG(B)
                  D=AIMAG(A)+REAL(B)
                  NUM=CMPLX(C,D)
                  A=ZZ*COSH(E)*COS(F)+ZL*SINH(E)*COS(F)
                  B=ZZ*SINH(E)*SIN(F)+ZL*COSH(E)*SIN(F)
                  C=REAL(A)-AIMAG(B)
                  D=AIMAG(A)+REAL(B)
                  DENOM=CMPLX(C,D)
                  ZS=NUM/DENOM
                  RETURN
                  END
```

LISTING OF SUBROUTINE IMPDNS

```
FORTRAN IV G LEVEL  21              MAIN              DATE = 74281          09/52/49              PAGE 0001

      C
      C
            SUBROUTINE EMF (ES,ZS,L,ER)
            COMPLEX ES,ZS,ZO,ER,C,D,E
            COMMON/IMPEMF/ZO,ALPHA,BETA
            A=ALPHA*L
            B=BETA*L
            C=ZS*COSH(A)*COS(B)-ZO*SINH(A)*COS(B)
            D=ZS*SINH(A)*SIN(B)-ZO*COSH(A)*SIN(B)
            F=REAL(C)-AIMAG(D)
            G=AIMAG(C)+REAL(D)
            E=CMPLX(F,G)
            ER=ES*E/ZS
            RETURN
            END
```

LISTING OF SUBROUTINE EMF

are made to the routines in the second tier: LCELLZ, RCELLZ, LVOLT, and RVOLT. Each of these subroutines controls the calculation sequence within a given cell, making calls to the four service routines, IMPDNS, EMF, ZFORM, and VFORM when appropriate. IMPDNS and EMF exercise the transmission line translational relationships for impedance and voltage, respectively. VFORM and ZFORM transform voltages and impedances through each of the two transformers that may be contained in a stub.

The complex voltages and impedances calculated by the above procedure for each relevant harmonic of the input waveform are stored in memory. When all values have been found, the voltage phasors are written onto a 9-track magnetic tape for later use by the plotting routine, PLMOD2. The power transfer ratios from the transmitter to the receivers are then calculated and printed along with the complex impedances previously determined.

<u>Input Data Format</u> - The input data required by the program, including format and card column designations, is shown in Figure I.3. The column marked "Data Card Number" refers to the order in which the data cards appear in the source deck.

<u>Output Formats</u> - In addition to the complex voltages written on magnetic tape, TPMOD2 produces hard copy listings of the following:

a) The input data, including the calculated value of the cable characteristic impedance and the number of odd harmonics considered. (See Figure I.4.)

b) The driving point impedance seen by the transmitter as a function of frequency (Figure I.5).

c) The driving point impedance of a detached stub as seen by the main bus (Figure I.6).

d) The driving point impedance looking into each junction of a stub and the main bus. For cells to the left of the transmitter, this corresponds to $\vec{Z}(5)$ of Figure 5, while for cells on the right this is $\vec{Z}(4)$ of Figure 4. In the transmitter cell this impedance corresponds to $\vec{Z}(4)$ in parallel with $\vec{Z}(5)$. Also included is the power loss from the transmitter to the junction, both as a function of frequency and total (Figure I.7).

e) The power loss from the transmitter to each receiving RTU, combined and as a function of frequency. This data, shown in Figure I.8, is an essential input to the determination of required transmitter power levels.

DATA CARD NUMBER	VARIABLE NAME	DESCRIPTION	CARD COLUMNS	FORMAT	COMMENTS
1	N1(1)	TRANSFORMER T1 PRIMARY TURNS	1 - 5	F5.2	N_1 OF FIG. 2
	N2(1)	T1 SECONDARY TURNS	6 - 10	F5.2	N_2 OF FIG. 2
	TR1(1)	T1 PRIMARY RESISTANCE (Ω)	11 - 15	F5.2	R_P OF FIG. 2
	TR2(1)	T1 SECONDARY RESISTANCE	16-20	F5.2	R_S OF FIG. 2
	TL1(1)	T1 PRIMARY LEAKAGE INDUCTANCE	21 - 30	E10.4	L_P OF FIG. 2
	TL2(1)	T1 SECONDARY LEAKAGE INDUCTANCE	31 - 40	E10.4	L_S OF FIG. 2
	TLM(1)	T1 MAGNETIZING INDUCTANCE	41 - 50	E10.4	L_M OF FIG. 2
2	N1(2)	T2 PRIMARY TURNS	1 - 5	F5.2	SAME AS ABOVE
	N2(2)	T2 SECONDARY TURNS	6 - 10	F5.2	
	TR1(2)	T2 PRIMARY RESISTANCE	11 - 15	F5.2	
	TR2(2)	T2 SECONDARY RESISTANCE	16 - 20	F5.2	
	TL1(2)	T2 PRIMARY LEAKAGE INDUCTANCE	21 - 30	E10.4	
	TL2(2)	T2 SECONDARY LEAKAGE INDUCTANCE	31 - 40	E10.4	
	TLM(2)	T2 MAGNETIZING INDUCTANCE	41-50	E10.4	
3	R	CABLE SERIES RESISTANCE / FOOT	1 - 12	E12.6	UNIT OF LENGTH IS ARBITRARY AS LONG AS ALL ARE EQUAL ; CHARACTERISTIC IMPEDANCE Z_0 IS CALCULATED INTERNALLY BY THE SIMULATION
	IND	CABLE SERIES INDUCTANCE/FOOT	13 - 24	E12.6	
	G	CABLE SHUNT CONDUCTANCE/ FOOT	25 - 36	E12.6	
	C	CABLE SHUNT CAPACITANCE / FOOT	37 - 48	E12.6	
	T	INPUT PULSE WIDTH (SECONDS)	49 - 60	E12.6	
	MAXHAR	MAXIMUM NUMBER OF HARMONICS ALLOWABLE	61 - 63	I3	SEE NOTE AT " PERCNT" ON CARD # 4

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Figure I.3 TPMOD2 INPUT DATA CARD FORMAT

DATA CARD NUMBER	VARIABLE NAME	DESCRIPTION	CARD COLUMNS	FORMAT	COMMENTS
4	TRISE	INPUT PULSE RISE TIME	1-12	E12.6	FOR FOURIER SERIES PRESENTLY USED TRISE ≡ TFALL ; MEASURED FROM 0-100%
	TFALL	INPUT PULSE FALL TIME	13-24	E12.6	
	PERCNT	PERCENT ENERGY CUTOFF FOR INPUT HARMONIC GENERATOR	25-36	E12.6	HARMONICS OF INPUT WAVEFORM ARE GENERATED UNTIL ENERGY FALLS BELOW THIS PERCENT OF THE FUNDAMENTAL'S ENERGY
	ZGEN	INPUT WAVEFORM GENERATORS	37-48	E12.6	Re [ZGEN]
		INTERNAL IMPEDANCE	49-60	E12.6	Im [ZGEN]
5	LAST	NUMBER OF LAST CELL ON RIGHT	1-2	I2	EQUIVALENT TO THE TOTAL NUMBER OF STUBS
	XMTR	NUMBER OF CELL CONTAINING TRANSMITTER	3-4	I2	CELLS NUMBERED FROM LEFT TO RIGHT
	RESI	LEFT BUS TERMINATION'S RESISTANCE	5-14	E10.4	EQUIVALENT TO RTERM
	LI	LEFT BUS TERMINATION'S INDUCTANCE	15-24	E10.4	GENERALLY = 0
	RLAST	RIGHT BUS TERMINATION'S RESISTANCE	25-34	E10.4	SAME AS ABOVE
	LLAST	RIGHT BUS TERMINATION'S INDUCTANCE	35-44	E10.4	
6-37*	R1(N)	TOP ISOLATION RESISTANCES	1-10	F10.0	TOTAL TOP ISOLATION RESISTANCE = 2* R1(N)
	R2(N)	BOTTOM ISOLATION RESISTANCES	11-20	F10.0	
	RSTUB(N)	STUB TERMINATION'S RESISTIVE COMPONENT	21-30	F10.0	DETERMINED BY THE RECEIVING RTU'S INPUT IMPEDANCE
	LSTUB(N)	STUB TERMINATION'S INDUCTIVE COMPONENT	31-40	E10.4	
	L(1,N)	CELL CABLE LENGTH	41-45	I5	SEE FIG 2
	L(2,N)	"	46-50	I5	
	L(3,N)	"	51-55	I5	
	TXFMR(N)	INDICATES IF TOP TRANSFORMER IS PRESENT	56-60	I5	= 1, TRANSFORMER PRESENT
	BXFMR(N)	INDICATES IF BOTTOM TRANSFORMER IS PRESENT	61-65	I5	= Ø, TRANSFORMER ABSENT

* ONE CARD CONTAINING THESE PARAMETERS IS REQUIRED FOR EACH OF THE N CELLS IN THE SYSTEM BEING SIMULATED

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Figure I.3 TPMOD2 INPUT DATA CARD FORMAT (CONT.)

```
*********** SERIAL NO. 09.53.51 ***********

INPUT QUANTITIES:

   CABLE CHARACTERISTICS  R=0.288000E-01 L=0.108900E-06 G=0.100000E-09  C=0.216000E-10
   PULSE WIDTH=0.999999E-06

   TRISE=0.400000E-07  TFALL=0.400000E-07  PERCENT CUTOFF= 0.10  GEN. IMPEDANCE=0.750000E 02+I(0.0          )

   CHARACTERISTIC IMPEDANCE = 0.71020386E 02 +I(-.14939566E 01)

   NUMBER OF CELLS= 32   XMTR IN CELL 14

   LEFT TERMINATION RES.=0.7100E 02     LEFT TERMINATION IND.=0.0

   RIGHT TERMINATION RES.=0.7100E 02     RIGHT TERMINATION IND.=0.0

   IN TRANSFORMER  1,N1= 2.50  N2= 1.00  R1=14.00  R2= 5.60  L1=0.7000E-05  L2=0.1100E-05  LM=0.1000E-01

   IN TRANSFORMER  2,N1= 1.00  N2= 1.85  R1=14.00  R2= 7.60  L1=0.7000E-05  L2=0.2100E-05  LM=0.1000E-01


   IN CELL  1
   L(1,N)= 11  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  2
   L(1,N)=  4  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  3
   L(1,N)=  7  L(2,N)=  5  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  4
   L(1,N)=  6  L(2,N)=  7  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  5
   L(1,N)=  9  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  6
   L(1,N)=  5  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  7
   L(1,N)=  5  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  8
   L(1,N)=  7  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL  9
   L(1,N)=  3  L(2,N)=  5  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=   54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

   IN CELL 10
```

FIGURE I.4

```
L(1,N)=  5  L(2,N)=  5  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 11
L(1,N)=  6  L(2,N)=  7  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 12
L(1,N)=  7  L(2,N)=  2  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 13
L(1,N)=  3  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 14
L(1,N)=  7  L(2,N)=  5  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 15
L(1,N)=  5  L(2,N)=  2  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 16
L(1,N)=  1  L(2,N)=  3  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 17
L(1,N)=  4  L(2,N)=  3  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 18
L(1,N)=  3  L(2,N)=  7  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 19
L(1,N)=  7  L(2,N)=  2  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 20
L(1,N)=  3  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 21
L(1,N)=  5  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 22
L(1,N)=  5  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 23
L(1,N)=  5  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 24
L(1,N)=  5  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 25
L(1,N)=  3  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=     0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1
```

FIGURE I.4 (Con't)

```
IN CELL 26
L(1,N)=  4  L(2,N)=  2  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 27
L(1,N)=  1  L(2,N)=  3  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 28
L(1,N)=  3  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 29
L(1,N)=  7  L(2,N)=  4  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 30
L(1,N)=  3  L(2,N)=  2  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 31
L(1,N)=  1  L(2,N)=  6  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1

IN CELL 32
L(1,N)=  7  L(2,N)=  8  L(3,N)= 20  LSTUB(N)=0.0        R1(N)=    54.  R2(N)=    0.  RSTUB(N)= 3730.  TXFMR= 1  BXFMR= 1
NUMBER OF HARMONICS CONSIDERED=   9

HIGHEST HARMONIC=  17
                                   ********** SERIAL NO. 09.53.51 **********
```

FIGURE I.4 (Con't)

DRIVING POINT IMPEDANCE AT XMTR/STUB JUNCTION .VS. FREQUENCY
XMTR IS IN CELL 14

HERTZ	OHMS	MAGNITUDE	ANGLE
.100E 07	170.09 +J(254.41)	306.03	56.23
.300E 07	382.67 +J(845.24)	927.83	65.64
.500E 07	581.66 +J(267.51)	640.22	24.70
.700E 07	131.47 +J(897.22)	906.80	81.66
.900E 07	84.64 +J(1389.32)	1391.89	86.51
.110E 08	74.93 +J(1830.43)	1831.96	87.66
.130E 08	76.21 +J(2281.55)	2282.82	88.09
.150E 08	94.83 +J(2828.01)	2829.60	88.08
.170E 08	444.55 +J(4265.13)	4288.23	84.05

********** SERIAL NO. 09.53.51 **********

FIGURE I.5

DRIVING POINT IMPEDANCE OF STUB 1 .VS. FREQUENCY

HERTZ	OHMS	MAGNITUDE	ANGLE
.100E 07	934.45 +J(-2050.66)	2253.53	-65.50
.300E 07	254.28 +J(-423.72)	494.16	-59.03
.500E 07	199.38 +J(120.31)	232.87	31.11
.700E 07	186.10 +J(502.02)	535.40	69.66
.900E 07	184.06 +J(847.32)	867.08	77.74
.110E 08	190.61 +J(1213.58)	1228.46	81.07
.130E 08	218.98 +J(1695.03)	1709.11	82.64
.150E 08	434.75 +J(2798.05)	2831.62	81.17
.170E 08	1735.93 +J(-2085.90)	2713.75	-50.23

********** SERIAL NO. 09.53.51 **********

FIGURE I.6

NODE DRIVING POINT IMPEDANCE .VS. FREQUENCY FOR CELL 1

HERTZ	OHMS	MAGNITUDE	ANGLE	POWER RATIO(DB)
.100E 07	70.33 +J(-2.03)	70.36	-1.65	-13.99
.300E 07	65.48 +J(-7.62)	65.92	-6.64	-15.96
.500E 07	55.62 +J(6.98)	56.04	7.05	-25.44
.700E 07	67.16 +J(7.33)	67.61	6.65	-14.99
.900E 07	69.54 +J(5.27)	69.74	4.34	-15.66
.110E 08	70.27 +J(3.76)	70.37	3.06	-16.68
.130E 08	70.57 +J(2.68)	70.63	2.17	-17.05
.150E 08	70.70 +J(1.55)	70.72	1.25	-15.36
.170E 08	69.77 +J(-1.54)	69.79	-1.27	-12.41

POWER RATIO=(POWER AT THIS NODE)/(REFERENCE POWER) IN DB
THE REFERENCE POWER IS THE XMTR OUTPUT POWER.

TOTAL POWER RATIO(DB)= -14.16

********** SERIAL NO. 09.53.51 **********

FIGURE I.7

POWER RATIO AT RECEIVERS (DB)

RECEIVER	COMBINED	** HARMONIC ** 1	3	5	7	9	11	13	15	17
1	-33.78	-33.76	-31.87	-39.20	-36.90	-42.03	-45.17	-45.75	-41.93	-31.11
2	-33.77	-33.75	-32.05	-38.40	-36.33	-41.64	-44.88	-45.55	-41.82	-31.00
3	-33.76	-33.75	-32.34	-36.04	-35.53	-41.57	-45.12	-45.82	-41.95	-30.93
4	-33.74	-33.78	-32.22	-34.28	-35.70	-41.92	-44.98	-45.45	-41.73	-30.70
5	-33.70	-33.83	-31.39	-32.73	-36.11	-41.36	-44.90	-45.82	-41.82	-30.73
6	-33.68	-33.86	-30.80	-32.13	-35.61	-41.22	-44.99	-45.30	-41.61	-30.59
7	-33.64	-33.90	-30.36	-31.23	-34.71	-41.29	-44.51	-45.36	-41.83	-30.55
8	-33.55	-33.95	-29.93	-29.52	-34.30	-41.34	-44.87	-45.54	-41.60	-30.40
9	-33.49	-33.97	-29.85	-28.54	-34.55	-41.11	-44.87	-45.04	-41.69	-30.46
10	-33.34	-33.99	-29.85	-26.96	-34.72	-40.72	-44.23	-45.49	-41.55	-30.14
11	-33.10	-33.99	-29.80	-25.37	-34.31	-40.96	-44.64	-45.29	-41.63	-30.21
12	-32.76	-33.94	-29.39	-23.90	-33.69	-41.06	-44.48	-45.43	-41.53	-30.14
13	-32.63	-33.91	-29.21	-23.43	-33.55	-40.72	-44.08	-45.53	-41.48	-30.18
15	-32.78	-33.95	-29.04	-24.06	-33.79	-40.29	-44.90	-44.63	-40.82	-30.06
16	-32.93	-33.99	-29.08	-24.67	-33.89	-40.58	-45.20	-44.45	-40.80	-30.00
17	-33.20	-34.07	-29.19	-25.84	-33.95	-41.38	-45.40	-44.53	-41.45	-30.26
18	-33.37	-34.13	-29.24	-26.67	-34.02	-41.75	-45.01	-45.04	-41.50	-30.36
19	-33.66	-34.22	-29.19	-28.73	-35.02	-41.09	-45.36	-44.70	-41.42	-30.34
20	-33.72	-34.23	-29.17	-29.34	-35.40	-40.89	-45.64	-44.60	-41.64	-30.56
21	-33.82	-34.24	-29.35	-30.51	-35.51	-41.41	-45.10	-45.30	-41.09	-30.35
22	-33.88	-34.21	-29.69	-31.57	-35.19	-42.19	-45.15	-44.86	-41.70	-30.80
23	-33.94	-34.15	-30.36	-33.12	-35.19	-41.67	-45.84	-45.03	-41.16	-30.49
24	-33.97	-34.08	-31.02	-34.79	-35.77	-41.19	-45.35	-45.36	-41.67	-31.03
25	-33.98	-34.03	-31.56	-36.21	-36.31	-41.46	-45.07	-44.78	-41.55	-30.77
26	-33.97	-33.97	-32.12	-37.86	-36.68	-42.24	-45.58	-44.96	-41.26	-31.01
27	-33.97	-33.95	-32.31	-38.43	-36.65	-42.42	-45.81	-45.24	-41.42	-31.23
28	-33.96	-33.91	-32.68	-39.41	-36.36	-42.31	-45.88	-45.45	-41.77	-31.24
29	-33.93	-33.85	-32.85	-42.26	-36.61	-41.99	-45.62	-45.11	-41.47	-31.29
30	-33.91	-33.84	-32.60	-43.95	-37.30	-42.25	-45.81	-45.36	-41.70	-31.42
31	-33.91	-33.84	-32.51	-44.48	-37.53	-42.32	-45.82	-45.37	-41.74	-31.31
32	-33.92	-33.85	-32.27	-45.84	-38.29	-42.73	-46.01	-45.41	-41.73	-31.52

POWER RATIO=(RECEIVER POWER/XMTR OUTPUT POWER) IN DB.

********** SERIAL NO. 09.53.51 **********

FIGURE I.8

The information supplied by these tables, when combined with the waveform plots produced by PLMOD2, provided an essentially complete picture of the performance that can be expected from a proposed multiplexed bus.

Part 3: Description of PLMOD2 - The purpose of PLMOD2 is to reconstruct and plot the voltage waveforms at the points considered by TPMOD2. The operation of the program is shown in the flow chart of Figure I.9 and the listing which immediately follows.

Input Data - Input to the plotting routine comes from two sources. The 9-track magnetic tape produced by TPMOD2 provides the harmonic voltage amplitudes and phases required to reconstruct the waveforms. Selection of the waveforms to be plotted, the number of time increments per pulse period, and designation of the reference voltage in the transmitter cell are all entered as data cards in the source deck. A listing of the elements contained on these cards is shown in Figure I.10.

Output Format - PLMOD2 produces two types of output data. A 7-track magnetic tape containing machine instructions for the off-line plotter is generated during execution of the program. The plots ultimately produced from this tape have the format of those in Figure 8, of Section V. As an adjunct to these waveform plots PLMOD2 lists the voltage arrays that correspond to the N discrete points plotted, where N is the number of time increments. An example of this listing is shown in Figure I.11.

Part 4: Operational Steps - The chart shown in Figure I.12 briefly describes the sequence of steps required to exercise the program as written on a computer facility equivalent to the author's.

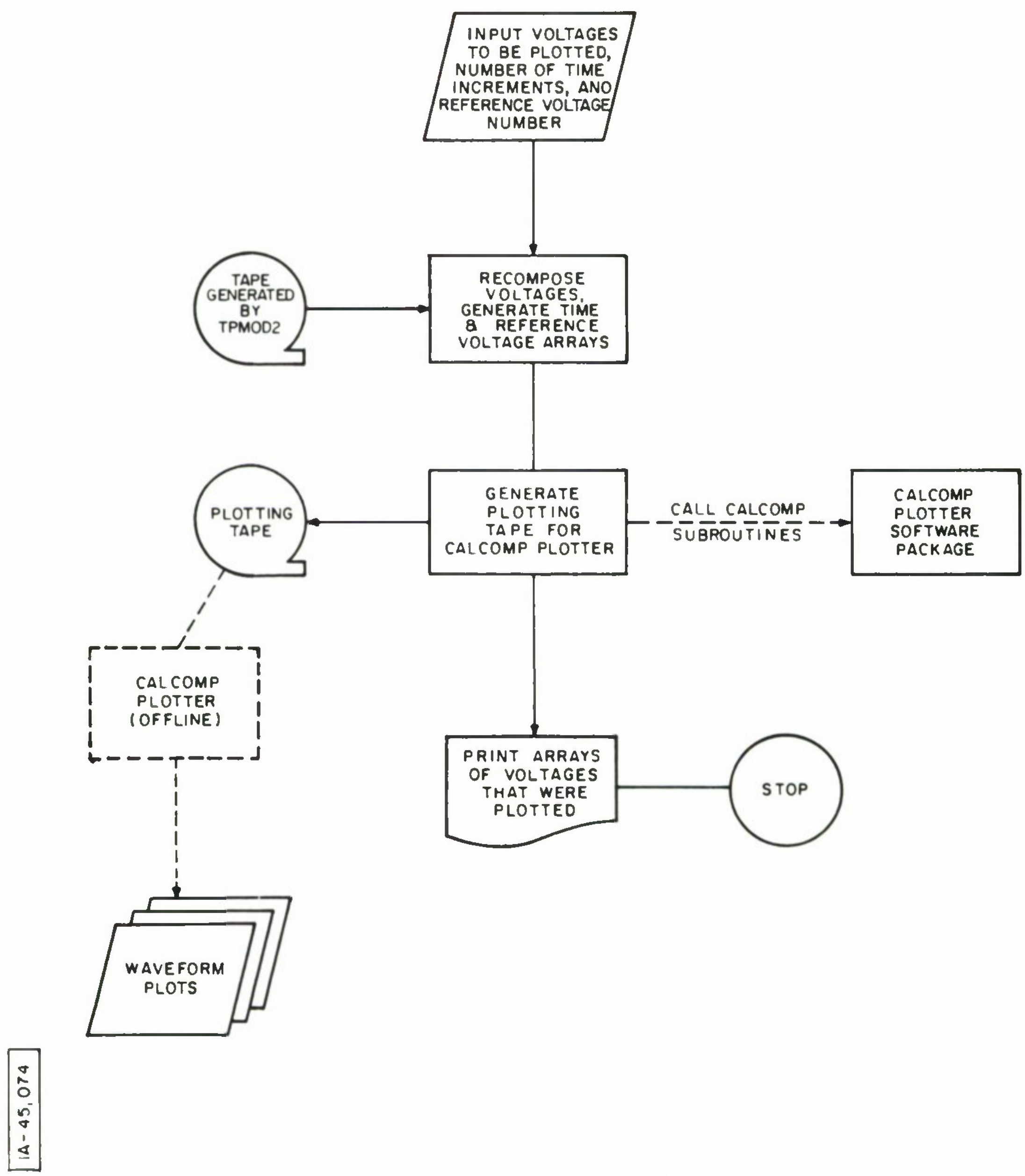

Figure I.9 FLOW CHART OF PLMOD2

```
C      THIS PROGRAM RECOMPOSES THE OUTPUT OF TPMOD2
C      INTO THE TIME DOMAIN. THE VOLTAGE WAVEFORMS
C      ARE THEN PRESENTED IN BOTH TABULAR AND CALCOMP
C      PLOT FORMATS.
C
C
C
C
       COMPLEX E(30,9,32)
       INTEGER CELL,CELLKT,VLT,SERIAL,DDDD,XMTR,VOLT,REFVLT
       DIMENSION V(100,9,32),CELL(32),VLT(32,9),SERIAL(2),DDDD(3),T(102),
      1XMTRV(102),PLOTV(102),IBUF(2000)
       DATA V/28800*0.0/,VLT/288*0/
       CALL DATE (DDDD)
       CELLKT=0
       READ(11)SERIAL,LAST,XMTR,TM,NN
       READ(11)(((E(K,M,N),K=1,NN,1),M=1,9,1),N=1,LAST,1)
       READ(5,100)NTINCT
  100  FORMAT(I3)
       READ(5,105)REFVLT
  105  FORMAT(I2)
       N=1
    5  READ(5,110)(CELL(N),(VLT(N,M),M=1,9,1))
  110  FORMAT(1I2,9I1)
       IF(CELL(N).GT.50)GO TO 10
       CELLKT=CELLKT+1
       N=N+1
       GO TO 5
   10  CONTINUE
       XOMEGA=2.*3.14159265/TM
C
C      RECOMPOSE VOLTAGE PHASORS INTO THE TIME DOMAIN
C
       DO 50 N=1,CELLKT,1
       DO 40 M=1,9,1
       IF(VLT(N,M).EQ.0)GO TO 40
       DO 30 K=1,NN,1
       PHASE=ATAN2((AIMAG(E(K,VLT(N,M),CELL(N)))),REAL(E(K,VLT(N,M),CELL(
      1N))))
       DO 25 KT=1,NTINCT,1
       ANGLE=(2.*K-1.)*XOMEGA*KT*TM/NTINCT
       V(KT,VLT(N,M),CELL(N))=V(KT,VLT(N,M),CELL(N))+CABS(E(K,VLT(N,M),CE
      1LL(N)))*COS(ANGLE+PHASE)
   25  CONTINUE
   30  CONTINUE
   40  CONTINUE
   50  CONTINUE
C
C      GENERATE THE REFERENCE VOLT ARRAY
C
       N=CELLKT+1
       M=REFVLT
       VLT(N,M)=REFVLT
       CELL(N)=XMTR
       DO 57 K=1,NN,1
       PHASE=ATAN2((AIMAG(E(K,VLT(N,M),CELL(N)))),REAL(E(K,VLT(N,M),CELL(
      1N))))
       DO 55 KT=1,NTINCT,1
```

LISTING OF PLMOD2

```
0041            ANGLE=(2.*K-1.)*XOMEGA*KT*TM/NTINCT
0042            V(KT,VLT(N,M),CELL(N))=V(KT,VLT(N,M),CELL(N))+CABS(E(K,VLT(N,M),CE
               1LL(N)))*COS(ANGLE+PHASE)
0043         55 CONTINUE
0044         57 CONTINUE
          C
          C     LOAD THE TIME ARRAY
          C
0045            DELT=TM/NTINCT
0046            T(1)=DELT
0047            DO 60 I=2,NTINCT
0048         60 T(I)=T(I-1)+DELT
          C
          C     LOAD XMTR VOLTAGE ARRAY
          C
0049            DO 65 I=1,NTINCT,1
0050            XMTRV(I)=V(I,REFVLT,XMTR)
0051         65 CONTINUE
0052            CALL PLOTS(IBUF,2000)
0053            CALL SCALE(XMTRV,8.,NTINCT,1)
0054            FIR=XMTRV(NTINCT+1)
0055            DEL=XMTRV(NTINCT+2)
0056            IFRAME=0
          C
          C
          C     GENERATE THE PLOTS
          C
          C
0057            CALL PLOT(0.,-12.,-3)
0058            F=0.7
0059            CALL FACTOR(F)
0060            CALL SCALE(T,10.,NTINCT,1)
0061            CELLS=LAST
          C
          C     LOAD THE 'Y' ARRAY
          C
0062            DO 80 N=1,CELLKT,1
0063            DO 75 M=1,9,1
0064            IF(VLT(N,M).EQ.0)GO TO 75
0065            DO 70 I=1,NTINCT,1
0066            PLOTV(I)=V(I,VLT(N,M),CELL(N))
0067         70 CONTINUE
0068            CALL SCALE(PLOTV,8.,NTINCT,1)
          C
          C     ADJUST 'Y' SCALING IF NECESSARY
          C
0069            TEST=PLOTV(NTINCT+2)
0070            IF(TEST.LE.DEL) GO TO 82
0071            XMTRV(NTINCT+1)=PLOTV(NTINCT+1)
0072            XMTRV(NTINCT+2)=PLOTV(NTINCT+2)
0073            FIRST=PLOTV(NTINCT+1)
0074            DELTA=PLOTV(NTINCT+2)
0075            GO TO 84
0076         82 CONTINUE
0077            FIRST=FIR
0078            DELTA=DEL
0079            XMTRV(NTINCT+1)=FIR
0080            XMTRV(NTINCT+2)=DEL
```

LISTING OF PLMOD2 (Con't)

```
      PLOTV(NTINCT+1)=FIR
      PLOTV(NTINCT+2)=DEL
   84 CONTINUE
      IFRAME=IFRAME+1
      IF(IFRAME.GT.1)GO TO 71
      PX=0.0
      PY=1./F*5.5
      CALL PLOT(PX,PY,-3)
      GO TO 72
   71 CONTINUE
      PX=1./F*12.0
      PY=0.0
      CALL PLOT(PX,PY,-3)
   72 CONTINUE
      CALL AXIS(0.0,0.0,7HSECONDS,-7,10.0,0.0,T(NTINCT+1),T(NTINCT+2))
      CALL AXIS(0.0,-4.0,16HNORMALIZED VOLTS,16,8.0,90.0,FIRST,DELTA)
      CALL SYMBOL(0.0,4.5,0.14,12HPLOT DATE = ,0.0,12)
      CALL SYMBOL(999.0,999.0,0.14,DODD,0.0,8)
      CALL SYMBOL(5.50,4.5,0.14,24HTOTAL NUMBER OF CELLS = ,0.0,24)
      CALL NUMBER(999.0,999.0,0.14,CELLS,0.0,-1)
      CALL SYMBOL(3.00,5.0,0.21,12HSERIAL NO.  ,0.0,12)
      CALL SYMBOL(999.0,999.0,0.21,SERIAL,0.0,8)
      CALL SYMBOL(3.15,-4.5,0.21,18HMUX-BUS SIMULATION,0.0,18)
      XTCELL=XMTR
      XTVOLT=REFVLT
      CALL SYMBOL(0.0,-5.0,0.14,17HLINE = XMTR(CELL ,0.0,17)
      CALL NUMBER(999.0,999.0,0.14,XTCELL,0.0,-1)
      CALL SYMBOL(999.0,999.0,0.14,7H, VOLT ,0.0,7)
      CALL NUMBER(999.0,999.0,0.14,XTVOLT,0.0,-1)
      CALL SYMBOL(999.0,999.0,0.14,1H),0.0,1)
      RCCELL=CELL(N)
      RCVOLT=VLT(N,M)
      CALL SYMBOL(6.3,-5.0,0.14,17HDASH = RCVR(CELL ,0.0,17)
      CALL NUMBER(999.0,999.0,0.14,RCCELL,0.0,-1)
      CALL SYMBOL(999.0,999.0,0.14,7H, VOLT ,0.0,7)
      CALL NUMBER(999.0,999.0,0.14,RCVOLT,0.0,-1)
      CALL SYMBOL(999.0,999.0,0.14,1H),0.0,1)
      CALL PLOT(0.,-4.,-3)
      CALL LINE(T,XMTRV,NTINCT,1,0,0)
      CALL DASHL(T,PLOTV,NTINCT,1,0,0)
      CALL PLOT(0.,4.,-3)
      IF(TEST.LE.DEL) GO TO 75
      CALL SYMBOL(3.4,2.7,0.21,14HALTERED Y-AXIS,0.0,14)
      CALL SYMBOL(3.6,2.2,0.21,12HSCALE FACTOR,0.0,12)
   75 CONTINUE
   80 CONTINUE
      CALL PLOT(14.0,0.0,999)
C
C     PRINT THE VOLTAGE ARRAYS
C
      WRITE(6,1000)SERIAL,DODD
 1000 FORMAT('1  SERIAL NO. ',2A4,' DATE IS ',2A4)
      WRITE(6,1002)TM,NTINCT,NN
 1002 FORMAT('0   PERIOD=',E10.4,'   # OF TIME INCREMENTS=',I5,
     1'   # OF ODD HARMONICS CONSIDERED=',I3)
      WRITE(6,1008)REFVLT
 1008 FORMAT('0   REFERENCE VOLTAGE IN XMTR CELL IS # ',I2)
      WRITE(6,1009)
```

LISTING OF PLMOD2 (Con't)

```
0135        1009  FORMAT(/,25X,'    ARRAY ELEMENTS ARE ORDERED FROM LEFT TO RIGHT',
                 1/,25X,'     AND TOP TO BOTTOM OF THE TABLES')
0136              DO 200 N=1,CELLKT,1
0137              WRITE(6,1010)CELL(N)
0138        1010  FORMAT('0 CELL ',I2)
0139              DO 190 M=1,9,1
0140              IF(VLT(N,M).EQ.0)GO TO 190
0141              VOLT=VLT(N,M)
0142              WRITE(6,1012)VOLT
0143        1012  FORMAT('0 VOLTAGE',I2)
0144              WRITE(6,1020)(V(I,VLT(N,M),CELL(N)),I=1,NTINCT,1)
0145         1020 FORMAT(' ',10F11.7)
0146          190 CONTINUE
0147          200 CONTINUE
            C
            C     PRINT THE REFERENCE VOLTAGE ARRAY
            C
0148              WRITE(6,1010)XMTR
0149              M=REFVLT
0150              WRITE(6,1012)M
0151              WRITE(6,1020)(V(I,M,XMTR),I=1,NTINCT,1)
0152              STOP
0153              END
```

LISTING OF PLMOD2 (Con't)

DATA CARD NUMBER	VARIABLE NAME	DESCRIPTION	CARD COLUMNS	FORMAT	COMMENTS
1	NTINCT	NUMBER OF TIME INCREMENTS PER PULSE PERIOD	1 - 3	I3	DETERMINES GRANULARITY OF PLOTS PRODUCED
2	REFVLT	NUMBER OF VOLTAGE IN TRANSMITTER CELL WHICH IS CONSIDERED THE REFERENCE. (e.g. 4 = V(4), 7 = V(7), ETC.)	1 - 2	I2	THE REFERENCE VOLTAGE IS PLOTTED ON EVERY PLOT TO GIVE A POINT OF COMPARISON FOR BOTH AMPLITUDE AND PHASE
3	CELL(N)	NUMBER OF CELL CONTAINING THE VOLTAGES TO BE PLOTTED	1 - 2	I2	CELL NUMBERS MUST BE RIGHT JUSTIFIED
	VLT(N,M)	THE NUMBER OF THE VOLTAGE IN CELL (N) TO BE PLOTTED	3	I1	THE NUMBERS OF THE VOLTAGES IN THIS CELL THAT ARE TO BE PLOTTED ARE ENTERED SEQUENTIALLY WITHOUT IMBEDDED BLANKS OR DELIMITERS
			4	I1	
			11	I1	(e.g. 12 372 = PLOT VOLTAGES V(3), V(7), & V(2) OF CELL # 12)
4→K (K ≤34)	EACH CARD HAS THE SAME FORMAT AS # 3 ABOVE. A FIXED NUMBER OF DATA CARDS IS NOT REQUIRED, BUT ONE CARD IS NEEDED FOR EACH CELL CONTAINING A VOLTAGE TO BE PLOTTED				
K + 1	—	A NUMBER >50 IS PLACED HERE AS A TRAILER TO SIGNIFY THE END OF THE DESIRED PLOT LISTING	1 - 2	I2	CUSTOMARILY = 99

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Figure I.10 PLMOD2 INPUT DATA CARD FORMAT

SERIAL NO. 15.20.46 DATE IS 10/04/74

PERIOD=0.1000E-05 # OF TIME INCREMENTS=100 # OF ODD HARMONICS CONSIDERED= 9

REFERENCE VOLTAGE IN XMTR CELL IS # 4

ARRAY ELEMENTS ARE ORDERED FROM LEFT TO RIGHT
AND TOP TO BOTTOM OF THE TABLES

CELL 1

VOLTAGE 7

-0.1470073	-0.1392342	-0.1269648	-0.1114267	-0.0941740	-0.0759029	-0.0562356	-0.0346134	-0.0113952	0.0118752
0.0333140	0.0518485	0.0676354	0.0817351	0.0946333	0.1062536	0.1160749	0.1238905	0.1301256	0.1354947
0.1404219	0.1448281	0.1484445	0.1512551	0.1535317	0.1557594	0.1573012	0.1594377	0.1604303	0.1610879
0.1616313	0.1623038	0.1629175	0.1631132	0.1627941	0.1622137	0.1617631	0.1614885	0.1610795	0.1602119
0.1589534	0.1577362	0.1562949	0.1562737	0.1553807	0.1539544	0.1524951	0.1515964	0.1513298	0.1504855
0.1470074	0.1392348	0.1269656	0.1114278	0.0941743	0.0759038	0.0562330	0.0346151	0.0113967	-0.0118747
-0.0333127	-0.0518473	-0.0676345	-0.0817352	-0.0946329	-0.1062533	-0.1160740	-0.1238899	-0.1301256	-0.1354945
-0.1404220	-0.1448290	-0.1484450	-0.1512551	-0.1535330	-0.1557592	-0.1573007	-0.1594373	-0.1604805	-0.1610875
-0.1616310	-0.1623040	-0.1629175	-0.1631132	-0.1627942	-0.1622127	-0.1617630	-0.1614863	-0.1610793	-0.1602117
-0.1589533	-0.1577356	-0.1562942	-0.1562729	-0.1553804	-0.1539340	-0.1524945	-0.1515957	-0.1513292	-0.1504853

CELL 32

VOLTAGE 7

-0.1426933	-0.1408881	-0.1365583	-0.1295311	-0.1204021	-0.1097522	-0.0970952	-0.0825559	-0.0652195	-0.0459276
-0.0256949	-0.0061853	0.0120134	0.0290243	0.0451922	0.0604520	0.0742697	0.0860142	0.0955560	0.1035731
0.1101434	0.1152078	0.1214900	0.1257317	0.1289218	0.1315649	0.1339053	0.1359767	0.1377916	0.1391589
0.1401486	0.1409896	0.1419223	0.1425956	0.1431130	0.1433531	0.1435004	0.1437349	0.1440695	0.1442931
0.1442454	0.1439907	0.1438096	0.1433697	0.1440155	0.1439158	0.1434475	0.1429052	0.1427226	0.1429030
0.1426932	0.1408880	0.1365587	0.1295816	0.1204824	0.1097526	0.0972954	0.0825567	0.0652203	0.0459292
0.0256962	0.0061367	-0.0120172	-0.0290232	-0.0451525	-0.0604515	-0.0742596	-0.0860133	-0.0955550	-0.1035778
-0.1101432	-0.1152078	-0.1214902	-0.1257315	-0.1289221	-0.1315552	-0.1339553	-0.1359767	-0.1377916	-0.1391587
-0.1401482	-0.1409890	-0.1419285	-0.1425955	-0.1431193	-0.1433531	-0.1435065	-0.1437343	-0.1440695	-0.1442983
-0.1442454	-0.1439905	-0.1438092	-0.1438692	-0.1440157	-0.1439155	-0.1434473	-0.1429044	-0.1427222	-0.1429027

CELL 14

VOLTAGE 4

0.2330322	0.2323235	0.2317497	0.2305030	0.2282338	0.2254024	0.2227435	0.2204371	0.2179282	0.2146213
0.2106793	0.2069855	0.2042341	0.2021322	0.1996544	0.1961747	0.1922395	0.1390356	0.1870111	0.1552036
0.1822602	0.1782544	0.1751425	0.1745926	0.1745391	0.1677001	0.1444111	0.0987425	0.0337550	-0.0382627
-0.1013463	-0.1437762	-0.1633008	-0.1665935	-0.1647293	-0.1662517	-0.1749722	-0.1997237	-0.2068080	-0.2223591
-0.2336960	-0.2397915	-0.2412677	-0.2399795	-0.2380982	-0.2370155	-0.2367892	-0.2365826	-0.2357031	-0.2342879
-0.2330319	-0.2323234	-0.2317494	-0.2305030	-0.2282338	-0.2254027	-0.2227441	-0.2204376	-0.2179287	-0.2146218
-0.2106795	-0.2069861	-0.2042348	-0.2021325	-0.1996547	-0.1961746	-0.1922406	-0.1390353	-0.1870109	-0.1552046
-0.1822604	-0.1782551	-0.1751410	-0.1745924	-0.1745384	-0.1677004	-0.1444144	-0.0987467	-0.0337599	0.0382585
0.1013426	0.1437746	0.1633006	0.1666994	0.1647238	0.1662511	0.1749709	0.1997223	0.2068065	0.2223532
0.2336959	0.2397927	0.2412694	0.2399812	0.2380994	0.2370168	0.2367901	0.2365837	0.2357042	0.2342889

FIGURE I.11

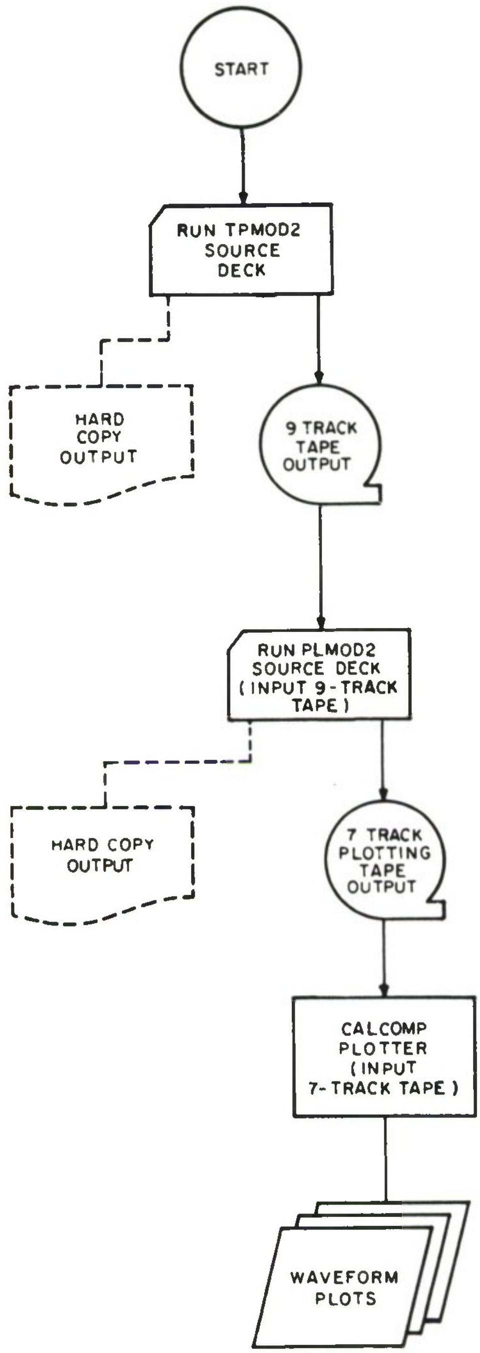

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Figure I.12 OPERATIONAL FLOW CHART

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